Crustal implications of bedrock geology along the Trans-Alaska Crustal Transect (TACT) in the Brooks Range, northern Alaska

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Abstract

Geologic mapping of the Trans-Alaska Crustal Transect (TACT) project along the Dalton Highway in northern Alaska indicates that the Endicott Mountains allochthon and the Hammond terrane compose a combined allochthon that was thrust northward at least 90 km in the Early Cretaceous. The basal thrust of the combined allochthon climbs up section in the hanging wall from a ductile shear zone in the south through lower Paleozoic rocks of the Hammond terrane and into Upper Devonian rocks of the Endicott Mountains allochthon at the Mount Doonerak antiform, culminating in Early Cretaceous shale in the northern foothills of the Brooks Range. Footwall rocks north of the Mount Doonerak antiform are everywhere parautochthonous Permian and Triassic shale of the North Slope terrane rather than Jurassic and Lower Cretaceous strata of the Colville Basin as shown in most other tectonic models of the central Brooks Range. Stratigraphic and structural relations suggest that this thrust was the basal detachment for Early Cretaceous deformation. Younger structures, such as the Tertiary Mount Doonerak antiform, deform the Early Cretaceous structures and are cored by thrusts that root at a depth of about 10 to 30 km along a deeper detachment than the Early Cretaceous detachment. The Brooks Range, therefore, exposes (1) an Early Cretaceous thin-skinned deformational belt developed during arc-continent collision and (2) a mainly Tertiary thick-skinned orogen that is probably the northward continuation of the Rocky Mountains orogenic belt. A down-to-the-south zone of both ductile and brittle normal faulting along the southern margin of the Brooks Range probably formed in the mid-Cretaceous by extensional exhumation of the Early Cretaceous contractional deformation.

Introduction

The Brooks Range is a collisional orogenic belt that extends E-W across the width of Alaska north of the Arctic Circle (Figure 1). This mountain belt, the northwesternmost extension of the Cordilleran mountain belt of North America, consists of a north facing, thin-skinned, décollement-style fold-and-thrust belt to the north and a metamorphic core with blueschist-facies mineral assemblages and penetrative fabrics to the south. Interpretations of the crustal structure across the central Brooks Range and the North Slope foreland (Colville) basin to the north of the orogenic belt have been offered in cross sections by *Mull et al.* [1987a], *Oldow et al.* [1987], *Mull and Adams* [1989], *Grantz et al.* [1991], *Moore et al.* [1994a], and *Blythe et al.* [1996]. The cross sections utilize principally the same reconnaissance-scale map sources [*Brosgé et al.* 1960, 1979a, b; *Brosgé and Reiser,* 1964, 1971; *Dillon et al.,* 1986] and share similar depictions of middle Paleozoic to Mesozoic rocks thrust over Cretaceous rocks along a basal detachment that lies at a depth of 8 to 12 km beneath the northern Brooks Range. All of the sections require large amounts (>500 km) of shortening for the orogenic belt. Nonetheless, the sections differ in their portrayal of the metamorphic core of the Brooks Range, contacts with adjacent mid-Cretaceous sedimentary basins, kinematic history, and a number of other critical features.

Geologic investigations of the Trans-Alaska Crustal Transect (TACT) project of the U.S. Geological Survey were conducted along the Dalton Highway across the Brooks Range during 1988-1992 in conjunction with the TACT Brooks Range seismic experiment [*Levander et al.,* 1994; *Fuis et al.,* this issue; *Wissinger et al.,* this issue]. The goal of this work was to collect geologic data that bear on the crustal structure of the Brooks Range and interpretation of the seismic data. Because published crustal sections along the Dalton Highway were based primarily on the reconnaissance (1:200,000- and 1:250,000-scale) geologic maps discussed above, new geologic mapping at a scale of 1:63,360 was undertaken in a 20- to 40-km-wide corridor along the Dalton Highway (Figures 2 and 3). The stratigraphy of the northern Brooks Range and North Slope is relatively well understood, so studies in the northern part of the field area (Figure 3a) were focused on analysis of fold-and-thrust structures and stratigraphic relations critical to understanding the region's tectonic history. Stratigraphic relations in the metamorphic core of the range to the south (Figure 3b) are poorly understood due to severe deformation, metamorphic recrystallization, and poor age control. In this area, extensive efforts were made to characterize major stratigraphic and structural packages and to collect protolith age data and metamorphic cooling ages which might constrain structural interpretations. Mapping also emphasized important structural contacts to determine their roles in construction of the orogen. The new information provides detailed insight into the crustal structure of the Brooks Range and helps to resolve questions raised by the published cross sections about the tectonic evolution of the orogen.

This paper summarizes the new findings about the lithology, age, and structural relations of the rocks along about 180 km of the Dalton Highway from the Koyukuk Basin in the south to the northern Brooks Range foothills to the north. Among the important questions addressed in this paper are the nature of the contact between allochthonous and parautochthonous rocks in the northern part of the transect, the relation between the metamorphic core and the fold-and-thrust belt, the protolith ages and stratigraphy of the metamorphic rocks of the orogen, and the nature of the boundary of the orogen with its hinterland. The primary purpose of this paper is to provide a comprehensive view of the bedrock geology along the entire TACT profile from hinterland to foreland in the Brooks Range orogen.

Geologic Setting

North directed contractional deformation in the Brooks Range resulted initially from convergence between an island arc and the south facing (present coordinates) Arctic Alaska passive continental margin during the Mesozoic [*Roeder and Mull,* 1978; *Box,* 1985; *Mayfield et al.,* 1988; *Moore et al.,* 1994a]. Convergence began in the Middle and Late Jurassic with subduction of the ocean floor that lay between the island arc and the continent. Subduction generated an accretionary prism composed of oceanic crustal rocks emplaced structurally beneath mafic to ultramafic plutonic rocks (ophiolite) of the forearc region of the arc. By the Late Jurassic or earliest Cretaceous, subduction began to involve rocks of the continental margin and culminated in A-type subduction of the continental margin in the Early Cretaceous. The oceanic crustal rocks and ophiolite, collectively called the Angayucham terrane [*Jones et al.,* 1987], are exposed along the southern flank of the Brooks Range and in the structurally highest thrust sheets in the range. Rocks of the former continental margin, the Arctic Alaska superterrane of *Moore* [1992], underlie most of the Brooks Range and its foredeep, the Colville Basin (Figure 1). The Late Jurassic and Early Cretaceous convergence resulted in development of a penetratively deformed, high-pressure/low-temperature metamorphic belt in the southern Brooks Range and imbrication of shelfal sedimentary rocks in the northern Brooks Range. The cessation of this stage of thrusting in the Early Cretaceous is bracketed between the youngest strata involved in thrusting (Valanginian, ~130 Ma) and unconformably overlying strata (Aptian(?)-Albian, ~115 to 110 Ma) [*Mull,* 1985]. Renewed shortening beginning in the Early Tertiary and continuing to the present is recorded in the foreland-basin sedimentary rocks and has produced the northeastern salient of the Brooks Range [*Wallace and Hanks,* 1990; *O'Sullivan et al.,* 1993a]. Preorogenic plutonic rocks of Devonian age are present principally in the southern Brooks Range. Synorogenic or postorogenic plutonic rocks are absent in the Brooks Range.

In the subsurface of the North Slope and in exposures in the northeastern Brooks Range, the stratigraphy of the Arctic Alaska superterrane has been divided into three major sequences. In ascending order, these are the pre-Mississippian Franklinian sequence, the Mississippian to Lower Cretaceous Ellesmerian sequence, and the Lower Cretaceous to Cenozoic Brookian sequence [*Lerand,* 1973; *Grantz and May,* 1983]. The pre-Mississippian rocks consist predominantly of upper Proterozoic and lower Paleozoic argillite, quartz-rich clastic rocks, carbonate rocks, chert, mafic volcanic rocks, and sparse granitic rocks that, at least in part, share stratigraphic similarities to the Proterozoic and lower Paleozoic stratigraphic succession of the Canadian Cordillera [*Lane,* 1991]. The pre-Mississippian rocks of the Franklinian sequence, however, display mild to intense strain related to pre-Middle Devonian deformational events [*Anderson et al.,* 1994] that has obscured the original stratigraphic architecture of much of the Franklinian of the northeastern Brooks Range. For this reason, rocks of the Franklinian sequence are referred to herein as pre-Mississippian rocks. The rocks and structures of the pre-Mississippian package are truncated by a regional unconformity and are overlain by the Ellesmerian sequence.

The Ellesmerian sequence consists predominantly of marine shale, quartzose clastic rocks, and limestone that represent a >5-km-thick shelfal sequence deposited on a south facing passive margin [*Moore et al.,* 1994a]. Clastic strata in the Ellesmerian sequence are mature and were derived from a northern source area. The overlying Brookian sequence, in contrast, consists of immature clastic rocks that were derived from a southern source area in the Brooks Range. Most of the Brookian strata form the sedimentary foredeep fill of the Colville Basin, which is the youngest and thickest (>8 km) part of the foreland basin of the Brooks Range. A review of the Proterozoic to Cenozoic stratigraphy of northern Alaska is provided by *Moore et al.* [1994a].

Interpretations of crustal structure in the central Brooks Range show that progressively older rocks are involved in Mesozoic deformation southward across the orogen [*Mull et al.,* 1987a; *Oldow et al.,* 1987; *Grantz et al.,* 1991; *Moore et al.,* 1994a]. North of the northern Brooks Range range front, Lower Cretaceous foredeep strata are involved in the deformation. In the northern Brooks Range, deformed upper Paleozoic and Mesozoic sedimentary strata of the passive-margin succession, which are the outer shelf correlatives of the Ellesmerian sequence, comprise imbricated allochthons that have been mapped over extensive areas. The southern Brooks Range exposes deformed and metamorphosed lower and middle Paleozoic rocks.

Various systems have been employed to subdivide the geology of the Brooks Range orogen (Table 1). In this paper, we utilize terrane nomenclature that was originally defined by *Jones et al.* [1987] for the Brooks Range and subsequently modified by *Moore* [1992] and *Moore et al.* [1994a]. This nomenclatural system is helpful for specifying lithotectonic packages in poorly mapped areas and in seismic sections and cross sections. Although controversial [e.g., *Karl and Mull,* 1993], terrane nomenclature dovetails well with existing geologic maps of the region because the maps are mainly of reconnaissance style and commonly emphasize lithologic packages and not their bounding structures. Terrane nomenclature used here is that of *Moore* [1992]. The terrane nomenclature is employed for descriptive purposes only and does not imply origin by any specific genetic model.

The part of the TACT transect discussed in this paper crosses seven terranes, as well as the overlying deposits of the Colville Basin. From north to south, these include the North Slope terrane, Endicott Mountains terrane (allochthon), De Long Mountains terrane, Hammond terrane, Coldfoot terrane, and Slate Creek terrane, all of which form part of the Arctic Alaska superterrane [*Moore,* 1992] (Figures 1 and 2). The North Slope terrane comprises the parautochthonous and autochthonous rocks of the orogen, whereas regionally the Endicott Mountains and De Long Mountains terranes consist of stratigraphically defined allochthonous successions of Upper Devonian to Lower Cretaceous passive-margin strata. The Hammond and Coldfoot terranes are metamorphosed, and their sedimentary features are partly (Hammond) to completely (Coldfoot) obliterated by deformation and metamorphic recrystallization [*Till et al.,* 1988]. Near the south end of the transect, the Angayucham terrane dips southward beneath the mid-Cretaceous clastic rocks of the Koyukuk Basin. Although rocks of the Angayucham terrane compose large klippen that overlie the Endicott Mountains and De Long Mountains terranes in the western Brooks Range [*Mayfield et al.,* 1988], no klippe of the Angayucham terrane are present in the central Brooks Range along the TACT corridor due

Table 1. Geologic-Geographic Nomenclature for Northern Alaska

Terrane and Superterrane [*Moore*, 1992]	Subterrane and Terrane [*Jones et al.*, 1987; *Moore et al.*, 1994a]	Geologic Provinces [*Till et al.*, 1988; *Moore et al.*, 1994a]	Lithotectonic Units [*Oldow et al.* ,1987]	Stratigraphic Nomenclature in TACT Transect Area [*Mull and Adams*, 1989; *Moore et al.*, 1994a]
Colville Basin	Colville Basin	Colville Basin	Colville Basin	Nanushuk Group (Albian to Cen.) Torok Shale (Albian to Cen.) Fortress Mountain Formation (Albian)
Arctic Alaska superterrane	Arctic Alaska terrane		Arctic Alaska terrane	
North Slope terrane	North Slope subterrane	northeastern salient	outer domain	Kingak Shale (Jur. and L. Cret.) Shublik Formation (Trias.) Sadlerochit Group Ivishak Sandstone (Trias.) Echooka Formation (Perm.) Lisburne Group (Miss. and Penn.) Endicott Group Kayak Shale (Miss.) Kekiktuk Conglomerate (Miss.) Pre-Mississippian rocks
Endicott Mountains terrane (allochthon)	Endicott Mountains subterrane (allochthon)	crestal belt	outer domain, Endicott Mountains allochthon	Coquinoid limestone and shale unit (L. Cret.) Etivluk Group Otuk Formation (Trias.-Jur.) Siksikpuk Formation (Perm.) Lisburne Group (Miss. and Penn.) Endicott Group Kayak Shale (Miss.) Kanayut Conglomerate (U. Dev. and Miss.(?)) Noatak Sandstone (U. Dev.) Hunt Fork Shale (U. Dev.)
De Long Mountains terrane	De Long Mountains subterrane	disturbed belt	--	Okpikruak Formation (U. Jur. and L. Cret.) Etivluk Group (Trias. to Jur.)
Sheenjek River terrane	Sheenjek River subterrane	disturbed belt	--	Etivluk Group (Perm. to Jur.) Lisburne Group (Miss. and Penn.)
Hammond terrane	Hammond subterrane	central belt	inner domain, Skajit allochthon	Skajit Limestone (Prot(?).-Camb., Ord.-Dev.)
Coldfoot terrane	Coldfoot subterrane	schist belt	inner domain, schist belt	

Terrane and Superterrane [*Moore*, 1992]	Subterrane and Terrane [*Jones et al.*, 1987; *Moore et al.*, 1994a]	Geologic Provinces [*Till et al.*, 1988; *Moore et al.*, 1994a]	Lithotectonic Units [*Oldow et al.* ,1987]	Stratigraphic Nomenclature in TACT Transect Area [*Mull and Adams*, 1989; *Moore et al.*, 1994a]
Slate Creek terrane	Slate Creek subterrane	phyllite belt	inner domain, Rosie Creek allochthon	
Angayucham terrane	Angayucham terrane	greenstone belt	Angayucham terrane	

Abbreviations of age are Camb., Cambrian; Cen., Cenomanian; Dev., Devonian; Jur., Jurassic; L. Cret., Lower Cretaceous; Miss., Mississippian; Ord., Ordovician; Penn., Pennsylvanian; Perm., Permian; Prot., Proterozoic; Trias., Triassic; U. Dev., Upper Devonian; U. Jur., Upper Jurassic.

to a deeper level of erosion (Figure 1). Along the southern margin of the Brooks Range, the narrow, but laterally persistent, Slate Creek terrane lies between the Angayucham terrane and subjacent Coldfoot terrane. The Slate Creek terrane has been assigned to the Angayucham terrane [*Dillon,* 1989; *Patton et al.,* 1994] and the Arctic Alaska terrane [*Moore et al.*, 1994a]; however, as discussed later in this paper, we now believe this terrane to be a tectonic unit that represents a structural boundary between the Arctic Alaska superterrane and the Angayucham terrane.

Stratigraphy of the Terranes and Overlying Deposits of the Colville Basin

Colville Basin

Lithic clastic rocks of Cretaceous age are exposed in the northern part of the TACT transect, where they overlie the North Slope terrane and the allochthonous rocks of the Endicott Mountains allochthon. These Cretaceous clastic rocks consist of detritus derived from volcanic, sedimentary, and metamorphic sources that lay to the south and record the unroofing of the nascent Brooks Range [*Mull*, 1985]. The older part of the Colville Basin foredeep consists of gently folded strata of the Fortress Mountain Formation, Torok Formation, and Nanushuk Group (Figures 3a and 4). The younger part of the Colville Basin foredeep consists of the Sagavanirktok Formation, which is exposed north of the study area. Although the Kongakut Formation (Lower Cretaceous) was shown in the northern part of the TACT area by *Brosgé et al.* [1979a], we did not distinguish this unit because of stratigraphic problems described by *Moore et al.* [1994a] and *Mull et al.* [this issue]. We instead assigned rocks of this interval to either the Kingak Shale or Fortress Mountain Formation on the basis of composition and age.

In its southernmost exposures, the Aptian(?) and Albian Fortress Mountain Formation consists of a mostly poorly exposed lower unit of thin-bedded siltstone turbidites (>500 m) and an overlying conglomeratic unit (3000 m) that grades upward from turbidites into fan-delta deposits [*Crowder*, 1987; *Ryherd*, 1990]. In the western Brooks Range, the Fortress Mountain Formation rests unconformably on deformed allochthonous rocks [*Mull*, 1985; *Molenaar et al.,* 1988]. In Atigun Gorge along the TACT route, however, the base of the Fortress Mountain Formation is a fault that locally truncates an indeterminate amount of the Fortress Mountain Formation [*Mull et al.,* this issue] (see below). Sedimentary clasts in the Fortress Mountain consist mainly of volcanic rocks and chert with subordinate quartzite and other lithologies that indicate possible derivation from the Endicott Mountains allochthon and structurally higher units.

The Fortress Mountain Formation fines and thins northward and upward into the Albian Torok Formation, which consists of thin-bedded lithic turbidites that are poorly exposed along the TACT transect. At Slope Mountain, the Torok Formation is overlain by about 1000 m of middle Albian mudstone, sandstone, and pebble conglomerate of the Nanushuk Group (Albian to Cenomanian). The Nanushuk Group consists of fluvial-deltaic cycles that coarsen upward from prodelta shale into marine sandstone and overlying delta-plain deposits [*Huffman*, 1989]. The Nanushuk prograded from the south and west along the length of the Colville Basin and, at Slope Mountain, displays paleocurrents that show paleotransport to the north [*Huffman*, 1989]. Like the Fortress Mountain Formation, sandstones of the Nanushuk are rich in chert and volcanic detritus but are considerably more enriched in quartz and metamorphic detritus than the Fortress Mountain.

North Slope Terrane

Rocks of the North Slope terrane crop out in the northeastern part of the study area and in the Mount Doonerak antiform in the west central part of the transect (Figure 1). We discuss these areas separately below.

Northeastern part of transect. Although the North Slope terrane consists of pre-Mississippian rocks and the overlying Ellesmerian sequence (Figure 4), the pre-Mississippian rocks and the lowest part of the Ellesmerian sequence are not exposed in the northeastern part of the transect area. On the basis of along-strike exposures to the east northeast [*Reiser et al.*, 1971; *Brosgé et al.*, 1997], the pre-Mississippian rocks likely present at depth in the northeastern part of the TACT study area consist of broken formation and mélange of Cambrian metavolcanic rocks and Ordovician red radiolarian chert and argillite. About 150 km east of the TACT transect area, these deformed rocks are unconformably overlain by locally derived, coarse-grained clastic rocks of Middle Devonian age (Ulungarat Formation of *Anderson et al.* [1994]). The Middle Devonian clastic rocks are tilted and, in turn, unconformably overlain by quartz- and chert-rich clastic rocks of the Mississippian Kekiktuk Conglomerate, the lowest unit of the Ellesmerian sequence (Figure 4). Throughout the North Slope terrane, the Kekiktuk rests in profound angular unconformity on pre-Mississippian sedimentary and metasedimentary rocks, a characteristic feature of the terrane.

Of particular significance to surface structural relations along the transect are the stratigraphy of the Lisburne Group and the overlying Sadlerochit Group of the Ellesmerian sequence. These intervals contain key lithostratigraphic features that allow distinction of allochthonous rocks of the Endicott Mountains allochthon from parautochthonous rocks of the North Slope terrane (see below).

The North Slope Lisburne Group is a structurally competent unit of widely exposed carbonate rocks. The Lisburne consists of a lower interval (~250 m) of dark, thin- to medium-bedded argillaceous limestone and grainstone that grades upward into an interval (~250 m) of light gray to pink, massive carbonate grainstone and packstone. In the northeastern Brooks Range, where it is well studied, the lower part of the Lisburne Group (Alapah Limestone) is upper Mississippian (Meramecian and Chesterian), whereas the upper part (Wahoo Limestone) is largely Pennsylvanian (Morrowan and Atokan) [*Krumhardt et al.*, 1996]. In contrast, strata of Pennsylvanian age in the Endicott Mountains allochthon are only a few meters thick or are missing [*Dumoulin et al.,* this issue].

Detailed stratigraphic work on the Lisburne Group has not been undertaken in the area of the transect, but a partial section (K.E. Adams and K.M. Cooper, unpublished data, 1992) (Figures 2 and 3a, measured section A; Figure 5) that includes at least the uppermost 145 m of the Lisburne was measured near the southern limit of the North Slope terrane east of Atigun Gorge. Conodont and megafossil ages from this section show that a significant thickness of Pennsylvanian strata—at least the upper 80 m and perhaps all of the measured section—is present in the Lisburne of this area, suggesting a closer affinity with the Lisburne of the northeastern Brooks Range than with the Lisburne of the Endicott Mountains allochthon. This section provides evidence that Lisburne Group rocks of the Endicott Mountains allochthon are constrained to locations south of the section (Figure 2 and 3a).

The Sadlerochit Group is present only in the North Slope terrane and is divided into the basal Echooka Formation and the overlying Ivishak Formation (Figure 4). Partial sections of the Echooka are commonly preserved in synforms and between thrust imbricates of the Lisburne in the northern part of the study area. A measured section of Permian rocks near Accomplishment Creek [*Adams,* 1991] (Figures 2 and 3a, measured section B) shows that the Echooka in the Accomplishment Creek area consists of a ~140-m-thick, fining-upward succession of fossiliferous, bioturbated siltstone to silty carbonate and dark shale that rests disconformably on carbonate rocks of the Lisburne Group (Figure 6). On the basis of lithology, bedding character, faunal assemblage, and biogenic and sedimentary structures, the Accomplishment Creek section documents the upward transition from storm-dominated deposition to suspension sedimentation with water depths no deeper than middle shelf.

The overlying Ivishak Formation consists of an upward thickening sequence of more than 30 m of fissile, dark gray to black, bioturbated quartzose siltstone capped by about 10 m of gray to black, resistant, thin-bedded, very fine grained quartz sandstone. Abundant ripple marks, bioturbation, and organization of lithofacies suggest that the Ivishak in this area represents marine-bar deposits. The Ivishak can be traced southward along the range front in the northeastern part of the transect area to east of Atigun Gorge, just west of the partial measured section of Lisburne Group strata described above (Figures 2 and 3a, measured section A), but it is not present in the Endicott Mountains allochthon (Figure 3a). Thus the distribution of the Ivishak constrains the southward extent of the North Slope terrane to approximately the same position as the measured Pennsylvannian strata of the Lisburne Group.

North Slope sequence in Mount Doonerak antiform. The similarity of the stratigraphy within the Mount Doonerak antiform to that of the North Slope subsurface was first reported by *Dutro et al.* [1976] and is shown in Figure 7. Pre-Mississippian rocks in the Mount Doonerak antiform consist of structurally complex units of Cambrian argillite and limestone, Ordovician and Silurian black phyllite, undated fine-grained black quartzite, and pillowed and fragmental porphyritic volcanic rocks. The volcanic rocks are cut by diabase dikes that yield Ordovician K-Ar hornblende ages and display chemical patterns indicative of arc magmatism [*Moore*, 1987; *Julian*, 1989] (Figure 8a). The pre-Mississippian rocks are unconformably overlain by quartzite of the Mississippian Kekiktuk Conglomerate, followed by Mississippian to Triassic units, including the Kayak Shale, Lisburne Group, Sadlerochit Group, and, locally, the Shublik Formation and Karen Creek Sandstone [*Mull et al.*, 1987b]. The facies, biostratigraphy, and presence of a relatively thin (~15 m) succession of Pennsylvanian strata in the Lisburne in the Mount Doonerak antiform indicate affinity with the North Slope terrane in a position intermediate to that of the Endicott Mountains allochthon [*Mull et al.*, 1987b].

Endicott Mountains Allochthon

The Endicott Mountains allochthon in the TACT transect lies north of the Mount Doonerak antiform and south of Atigun Gorge (Figure 2). The allochthon is defined by a distinctive stratigraphic succession that has clear stratigraphic affinity with the Ellesmerian sequence of the North Slope terrane [*Mull*, 1982] (Figure 4). The succession of the Endicott Mountains allochthon is distinguished from the succession of the North Slope terrane by (1) a faulted base; (2) a thick, regressive Upper Devonian sequence; (3) finer grained Permian to Early Cretaceous strata; and (4) the absence of a sub-Mississippian unconformity (Figure 7). The faulted base of the allochthon is commonly placed beneath the Devonian Beaucoup Formation [e.g., *Mull et al.*, 1987b], but rocks of the Beaucoup are stratigraphically and structurally more complex than units in the Endicott Mountains allochthon, have a different structural trend, and are intimately associated with rocks of the Hammond terrane, as discussed below.

The lower part of the Endicott Mountains allochthon comprises a south facing fluvial-deltaic wedge of quartz- and chert-rich clastic detritus shed from a northern source area in the Late Devonian and Early Mississippian [*Nilsen*, 1981; *Moore and Nilsen*, 1984]. The clastic wedge has a maximum thickness of over 4 km and consists, in ascending order, of the Hunt Fork Shale, Noatak Sandstone, Kanayut Conglomerate, and Kayak Shale (Figure 9 and Table 2). Single-grain U-Pb ages of detrital zircon from a sandstone sample of Kanayut collected near Atigun Pass indicate that the clastic wedge was derived from a provenance with Archean, Proterozoic (2.0 to 1.8 and 1.5 to 1.0 Ga), and Devonian (370 to 360 Ma) zircons [*Aleinikoff et al.*, 1995]. The Devonian detrital zircons likely date sparse pebbles and grains of felsic volcanic rock present in the sample and provide a maximum age of Late Devonian for the Kanayut.

The clastic wedge is capped by an Early Mississippian transgressive sequence in the Kayak Shale and overlain by thick carbonate-platform deposits of the Lisburne Group. The lower part of the Lisburne was deposited in a shallow-water platform environment adjacent to carbonate shoals, whereas the upper part of the Lisburne was deposited under shallower conditions with more restricted circulation, including shallow subtidal and supratidal environments [*Dumoulin et al.*, this issue]. Conodonts indicate that the Lisburne is mainly Early Mississippian, although redeposited, relatively deeper water, open-marine conodonts of Pennsylvanian (Morrowan and/or Atokan) age are locally present in the

Table 2. Stratigraphic Data for Endicott Mountains Allochthon in Vicinity of TACT Study Area, Central Brooks Range

Unit	Thicknes s, m	Lithology	Depositional Environment	Age	Comments
			North of Toyuk Thrust		
Coquinoid limestone and clay shale	<10	brown clay shale with sparse 1- to 2-m-thick coquina beds	middle to outer shelf	Early Cretaceous (Neocomian)	*Buchia sublaevis* in coquina beds indicates Valanginian age
Otuk Formation	~100	black, organic, nodular shale; fossiliferous silicified mudstone and gray weathering limestone; and dark, calcareous siltstone	middle to outer shelf	Triassic to Jurassic	limestone is Late Triassic, commonly silicified, and contains abundant *Monotis* sp. pelecypods
Siksikpuk Formation	130	basal pyritic siltstone overlain by variegated concretionary shale; contains 1-m-thick siliceous mudstone interval	transgressive storm-influenced marine deposits; no deeper than middle shelf	Permian (Wolfcampian to Guadalupian)	disconformably overlies platform carbonate rocks of Lisburne Group
Lisburne Group	650 to >1000	argillaceous grainstone and packstone in lower part, grading to massive wackestone in upper part	carbonate platform; shallow marine in lower part to subtidal and supratidal at top	Early Mississippian (Kinderhookian) to Middle Pennsylvanian (Atokan)	conodonts indicate Kinderhookian to Chesterian for most of unit; Pennsylvanian strata at top are only locally preserved and <10 m thick where present
Kayak Shale	210	black shale, with fine-grained sandstone at base and intercalated limestone beds in upper part	transgressive marine deposits; intertidal to shelf	Early Mississippian (Kinderhookian)	conodonts near top of unit are late Kinderhookian
Kanayut Conglomerate	2876	fining-upward sequences of channelized conglomerate, sandstone, and shale in lower and upper members; channelized conglomerate and sandstone in middle member	meandering stream in lower and upper members; gravelly braided stream in middle part	Late Devonian (Famennian) and Early Mississippian(?)	divided into three formal members —Ear Peak, Shainin Lake, and Stuver— by *Nilsen and Moore* [1984]
Noatak Sandstone	0 to 200	sandstone and interbedded siltstone	marginal marine	Late Devonian (Famennian)	
Hunt Fork Shale	500	thickening-up sequences of siltstone and interbedded sandstone	prodelta to marginal marine	Late Devonian	

Unit	Thicknes s, m	Lithology	Depositional Environment	Age	Comments
			South of Toyuk Thrust		
Coquinoid limestone and clay shale[1]	<10	brown clay shale with sparse 1- to 2-m-thick coquina beds	middle to outer shelf	Early Cretaceous (Neocomian)	*Buchia sublaevis* in coquina beds indicates Valanginian age
Otuk Formation[1]	~70	black, pyritic shale and yellow weathering fossiliferous siliceous mudstone and siliceous limestone	middle to outer shelf	Triassic to Jurassic	limestone is Late Triassic and contains abundant *Monotis* sp. pelecypods
Siksikpuk Formation[1]	80	basal pyritic siltstone overlain by variegated, concretionary cherty shale; contains up to 24-m-thick shaley chert interval	transgressive marine deposits; no deeper than middle shelf	Permian (?) (Wolfcampian(?) to Guadalupian(?))	disconformably overlies basinal facies of Lisburne Group
Lisburne Group[1]	<400	argillaceous wackestone and packstone and cherty dolostone; black shale, lime mudstone, and spiculitic chert in upper part	carbonate platform, slope, and starved basin	Mississippian	
Kayak Shale	>40	black shale	transgressive marine deposits; intertidal to shelf	Early Mississippian	late Kinderhookian conodonts from Kayak west of Atigun Pass
Kanayut Conglomerate	650	thinning-upward sequences of sandstone, 5 to 10 m thick	sandy braided stream	Early Mississippian(?) and Late Devonian (Famennian)	Famennian brachiopod from near top of unit 100 km west of transect; contains Archean, Proterozoic, and Devonian detrital zircons
Noatak Sandstone	350	sandstone and lesser siltstone	marginal marine	Late Devonian (Famennian)	contains both Frasnian and Famennian fossils outside TACT transect area

Unit	Thicknes s, m	Lithology	Depositional Environment	Age	Comments
Hunt Fork Shale	>1500	thin-bedded siltstone and lesser sandstone in lower part; thickening-up sequences of siltstone to sandstone in upper part; contains sparse limestone beds	mainly thin-bedded turbidites in lower part and prodelta turbidites and delta front deposits in upper part	Late Devonian (Frasnian and Famennian)	middle to late Frasnian conodonts at base and late Frasnian conodonts in lower part of unit; late Frasnian megafossils and conodonts in upper part near Atigun Pass; Famennian fossils in upper part outside of transect area

Sources are *Armstrong and Mamet* [1978]; *Brosgé et al.* [1979a]; *Moore et al.* [1989, 1994a]; *Nelson and Csejtey* [1990]; *Adams* [1991]; *Aleinikoff et al.*, [1995]; and *Adams et al.* [this issue]; *Dumoulin et al.* [this issue]

[1]Facies exposed 100 to 200 km west of TACT study area

uppermost few meters (<10 m) of the unit. These Pennsylvanian strata may have been deposited as lag concentrates along a drowning surface at the top of the Lisburne [*Dumoulin et al.,* this issue].

The uppermost part of the Endicott Mountains allochthon in the TACT study area consists of shale-rich units (Permian Siksikpuk and Triassic to Jurassic Otuk Formations of the Etivluk Group and Lower Cretaceous coquinoid limestone and clay shale unit) that have an aggregate stratigraphic thickness of ~250 m (Figure 9 and Table 2). The Siksikpuk Formation comprises a transgressive sequence that rests disconformably on the Lisburne Group. It is commonly exposed in imbricates with the Lisburne Group and along the range front. The Otuk and coquinoid limestone and shale unit disconformably overlie the Siksikpuk and are restricted to exposures along the range front [*Mull et al.,* this issue].

The shale-rich units of the Endicott Mountains allochthon are distinctly thinner, finer grained, and thinner bedded than coeval units (Echooka Formation, Ivishak Sandstone, Shublik Formation, and Kingak Shale) of the North Slope terrane. The shale-rich units of the Endicott Mountains represent deposition on a southward deepening shelf in a more distal environment than the correlative units of the North Slope terrane [*Adams et al.,* this issue]. A measured section of the Siksikpuk Formation, completed as part of this study (Figures 2 and 3a, measured section C; Figure 6), is located less than 10 km south of a measured section of the Echooka Formation (Figures 2 and 3a, measured section B; Figure 6) and thus constrains the northern limit of the contiguous Endicott Mountains allochthon to within the 10-km region between the two sections of Permian rocks.

A prominent zone of thrusting, the Toyuk thrust system (Figures 2 and 3a), divides the Endicott Mountains allochthon into northern and southern parts that exhibit distinct stratigraphic differences (Figure 9 and Table 2). Some of the differences are as follows: (1) The Kanayut Conglomerate in the northern part of the allochthon is very thick (>2700 m), conglomeratic (maximum clast size of 15 cm), and divided into three members based primarily on the presence of intercalated shale in the upper and lower parts of the conglomerate [*Nilsen and Moore,* 1984]; in the southern part of the allochthon, the Kanayut is thinner (650 m), contains little conglomerate, and cannot be subdivided into members because shale is mostly absent. (2) The Hunt Fork Shale and Noatak Sandstone are thin north of the Toyuk (~700 m), whereas both have much greater thickness south of the thrust system (>1850 m). (3) Thin-bedded basinal deposits are abundant in the lower part of the Hunt Fork south of the Toyuk but nearly absent north of the thrust system. (4) Although not exposed in the TACT transect area south of the Toyuk, both the Lisburne Group and Siksikpuk Formation are thinner and display notably deeper water facies south of the Toyuk than north of it [*Adams*, 1991; *Dumoulin et al*., this issue]. Taken together, these observations suggest that the Toyuk thrust system juxtaposes significantly different facies in most units in the Endicott Mountains allochthon and is thus likely the site of a relatively large amount of shortening within the Endicott Mountains allochthon.

De Long Mountains Terrane

Regionally, the De Long Mountains terrane comprises sedimentary allochthons that structurally overlie the Endicott Mountains allochthon (Figure 2). These allochthons consist principally of Devonian to Jurassic fine-grained clastic rocks, deep-marine carbonate rocks, and chert that are thought to be the distal equivalents of north sourced, age-correlative strata in the North Slope terrane and Endicott Mountains allochthon. The uppermost parts of this terrane consist of southerly derived lithic turbidite deposits of the Jurassic and Lower Cretaceous Okpikruak Formation, which are the early, syntectonic, foredeep deposits of the Brooks Range orogen [*Moore et al.,* 1994a].

Along the TACT transect, deformed, micaceous lithic turbidites of the Okpikruak Formation are exposed in a thin (<500 m) tectonic unit along the range front above the Endicott Mountains allochthon and beneath the Fortress Mountain Formation (Figure 3a). These deposits contain isolated tectonic blocks of chert and silicified mudstone that yield Middle and Late Triassic and Early Jurassic radiolarians [*Mull et al.,* this issue]. These blocks are correlative in age and lithology with chert and silicified mudstone deposits found in the De Long Mountains terrane in the western Brooks Range but not in the Endicott Mountains allochthon. The turbidite strata that enclose the blocks contain *Buchia sublaevis* fossils that are age correlative with the coquinoid limestone and shale unit at the top of the Endicott Mountains allochthon. These relations indicate that the Okpikruak in the TACT transect comprises a klippe of broken formation or mélange of the younger parts of the De Long Mountains terrane [*Mull et al.,* this issue].

Hammond Terrane

The Hammond terrane consists of phyllitic and metacarbonate rocks that are extensively exposed south of the Endicott Mountains allochthon and Mount Doonerak antiform in the metamorphic core of the Brooks Range (Figures 1 and 7). The Hammond is characterized by thick packages of Paleozoic carbonate rocks that are encased in generally fine grained metaclastic rocks. North of a regional synform near Snowden Mountain (Figure 2), the metaclastic and, locally, the metacarbonate rocks display abundant relict sedimentary features. South of the Snowden Creek synform, quartz- and mica-rich phyllites with rare sedimentary features dominate, and carbonate rocks are entirely marble. Correlations of rock units from the northern to the southern limb of the synform are mostly uncertain, and contacts between all of the major units of the Hammond are deformed and assumed to be faulted. Metamorphic assemblages replace primary minerals throughout most of the Hammond terrane and indicate metamorphism under greenschist-facies conditions. Hammond terrane rocks are structurally and stratigraphically complex, and little consensus exists over original stratigraphic relations.

The Hammond terrane is here subdivided into the Skajit Limestone and nine informally named, mainly metaclastic, units. The lithology, protoliths, and ages of these units are summarized in Table 3; other significant findings are noted below. The most prominent unit of the Hammond terrane is the Skajit Limestone, which forms conspicuous massifs along the TACT transect. The detailed results of TACT stratigraphic investigations of these rocks are presented in *Dumoulin and Harris* [1994] and are summarized in Figure 10. Where dated with fossils, the Skajit (Matthews River unit by *Dumoulin and Harris* [1994]) consists mainly of massive marble and dolostone of Late Ordovician and Silurian age and rare Lower and/or Middle Devonian strata. Whether the Devonian rocks are in gradational or unconformable contact with the Ordovician and Silurian strata is unknown. In southern exposures of the Skajit at Dillon and Sukakpak Mountains (Figure 2), fossils are absent and sedimentary features consist only of coated carbonate grains. *Dumoulin and Harris* [1994] inferred a Late Proterozoic and/or earliest Paleozoic age for these rocks on the basis of lithologic correlation with similar rocks elsewhere in the Hammond terrane. The Skajit may constitute dismembered pieces of a long-lived carbonate platform succession that began in the Proterozoic and continued into the Devonian [*Dumoulin and Harris*, 1994] (Figure 10). Fine-grained metaclastic rocks adjacent to the carbonate massif at Snowden Mountain [*Palmer et al.,* 1984; *Dillon et al.,* 1988] (Figure 2) include lower Middle Cambrian and Ordovician fossiliferous phyllitic rocks (Snowden Mountain and Snowden Creek units of *Dumoulin and Harris* [1994]). These units may represent clastic intervals in the carbonate platform succession [*Dumoulin and Harris,* 1994].

Although the metacarbonate rocks along the TACT transect have long been assigned to the Devonian Skajit Limestone [*Mertie,* 1925; *Brosgé et al.,* 1962; *Brosgé and Reiser,* 1964; *Dillon et al.,* 1988; *Dillon,* 1989], these rocks (1) consist largely of marble rather than limestone, (2) are older, in part, than the Devonian age generally ascribed to the Skajit Limestone [e.g., *Tailleur et al.,* 1967; *Dillon,* 1989], and (3) probably contain mappable metaclastic intervals (e.g., the Snowden Mountain and Snowden Creek phyllites) not originally included in the formation. Thus, the stratigraphy of the Skajit Limestone is poorly defined and in need of revision in light of the new information collected along the TACT transect.

Table 3. Stratigraphic Data for Hammond Terrane in TACT Study Area, Central Brooks Range

Unit	Thickness, m	Lithology	Protolith	Age
Unnamed metagraywacke and metaconglomerate	2000(?)	phyllitic, volcanogenic sandstone, and argillite, that thicken and coarsen upward into thick-bedded, coarse-grained sandstone and pebble conglomerate; contains relict graded bedding and sharp, erosional bases	thick-bedded, fine to coarse grained turbidites	Late Devonian (Frasnian)? or older
Dietrich River phyllite	1000(?)	dark gray slate and phyllite with prominent metalimestone units near base; intruded by sparse to abundant diabase bodies; contains rare sandstone beds to 5 cm thick; displays relict graded beds and laminations	shallow-marine limestone and shale at base, grading upward into thin-bedded, shale-rich turbidites; intruded by extensional mafic rocks	Middle(?) and Late Devonian; metalimestone near base contains Givetian(?) and early Frasnian conodonts(1) and megafossils(2)
Nutirwik Creek metavolcaniclastic rocks	>300	metamorphosed and deformed felsic to intermediate volcaniclastic rocks and sparse massive hypabyssal rocks, including micaceous purple and green phyllite, lithic-quartz-feldspar sandstone, argillite pebble conglomerate, and feldspar porphyry; capped by black, calcareous phyllite	volcaniclastic deposits shed from felsic volcanic arc into marine or partly marine environment; conodonts indicate nonvolcanic, basinal conditions at top of unit	yields Early Devonian U-Pb zircon ages (393±2 and 385±2 Ma) (3); conodonts indicate upper part is Late Devonian (middle Frasnian)(4)
Trembley Creek phyllite	500(?)	tan weathering metasandstone and argillite; contains abundant grains of detrital white mica; contains relict graded bedding and sharp, erosional bases	thin- to thick-bedded, fine to medium grained turbidites	Devonian or older; detrital white mica yielded Late Ordovician Ar-Ar age (~450 Ma)(5)
Skajit Limestone	>200	massive metalimestone, dolostone, and marble that display local graphitic zones and laminae and rare sedimentary structures and fossils	carbonate platform strata deposited under normal marine to slightly restricted conditions	primarily Late Ordovician and Silurian; also includes strata of Early and/or Middle Devonian and possibly Cambrian and/or Proterozoic age(1)
Jesse Mountain phyllite	>500	interlayered very fine grained quartz-white mica schist, quartzite, and brown weathering sandy marble	marine sandstone, shale, and minor sandy limestone	Devonian or older
Dusty Mountain phyllite	~500	thinly layered quartz-white mica-chlorite phyllite; contains rare thin, black limestone	marine shale; possibly correlative with Dietrich River phyllite	Devonian; limestone at base contains Middle or Late Devonian conodonts(4)
Snowden Creek phyllite	~200	black phyllite with intercalated metalimestone, metachert, and metasandstone	slope to basinal limestone and shale	Early and Middle Ordovician(1)

Unit	Thickness, m	Lithology	Protolith	Age
Snowden Mountain phyllite	~200	gray phyllite with sandy metalimestone, capped by bioclastic limestone	outer shelf or slope shale and limestone	early Middle Cambrian; limestone contains trilobites of Siberian affinity(6)
Vi Creek schist	~2000	laminated, very fine grained white mica-chlorite-quartz schist with sparse metacongomerate and marble	volcaniclastic rocks and quartz-rich sediments	Devonian or older; marble contains Ordovician to Triassic conodont(4)
Unnamed calcareous schist	~500	fine-grained, calcareous white mica-quartz schist	calcareous lutites	Devonian or older
Hammond River phyllonite	~1000	quartz-white mica phyllonite and local mylonite; contains lenses of very fine grained black quartzite	tectonic unit composed of fault slivers of adjacent units	Cretaceous deformational age

Sources are 1, *Dumoulin and Harris* [1994]; 2, R.B. Blodgett (unpublished data, 1990); 3, *Aleinikoff et al.* [1993]; 4, A.G. Harris (unpublished data, 1989, 1990); 5, P. Layer (unpublished data, 1991); 6, *Palmer et al.* [1984].

Metaclastic units north of the Snowden Creek synform consist principally of the Nutirwik Creek metavolcaniclastic rocks and the Dietrich River phyllite (Figures 3 and 7 and Table 3). The Nutirwik Creek metavolcaniclastic rocks comprise metamorphosed felsic to intermediate volcaniclastic rocks and sparse massive hypabyssal rocks that have yielded Early and Middle Devonian U-Pb zircon ages [*Aleinikoff et al.*, 1993] (Table 3). Euhedral crystals, clasts with relict volcanic textures, and feldspar-rich compositions in the metasandstones suggest a volcanogenic protolith for the Nutirwik Creek. Geochemical analyses indicate that the volcaniclastic strata are dacitic to rhyolitic, and the hypabyssal rocks are andesitic to basaltic. On elemental-abundance diagrams (Figure 11), the analyses show enrichment in large-ion-lithophile elements (LIL) and relative depletion in tantalum (Ta), indicating subduction-related volcanism [*Thompson et al.*, 1984]. West of Snowden Mountain, purple and green phyllite of the Nutirwik Creek metavolcaniclastic rocks is nearly concordent with an unnamed unit of greenish-gray volcanogenic metagraywacke and polymict conglomerate that has an apparent thickness approaching 2 km (Figure 3b and Table 3). In the Table Mountain area, a thin unit of black, calcareous phyllite near the top of the Nutirwik Creek (not shown in Figure 3b) contains conodonts and other fossils that indicate deposition under deep-marine conditions in the middle Frasnian (early Late Devonian) [*Dumoulin and Harris*, 1994]. Although the Nutirwik Creek metavolcaniclastic rocks are mostly fault bounded, volcanogenic strata of the unit appear to rest in depositional contact on the Skajit Limestone in a few places.

The Dietrich River phyllite consists predominantly of brown weathering, dark gray slate and phyllite with thin units of Givetian(?) (late Middle Devonian(?)) and early Frasnian (early Late Devonian) metalimestone near its base (Figures 7 and 12 and Table 3). The metalimestone typically forms lenticular, fossiliferous, shallow-marine units from 50 m to more than 6 km in length and 2 to 20 m thick. The slate and phyllite have been derived from metamorphosed mudstone and sparse, thin-bedded turbidites. The Dietrich River unit is intruded by sill, dike, or stock-like bodies of metadiabase and microgabbro that compose as much as 30% of the unit in some areas but are nearly absent elsewhere. The intrusive rocks have basaltic compositions and elemental-abundance patterns that are only slightly enriched in LIL elements relative to mid-oceanic ridge basalts (MORB) but display a slightly negative Ta anomaly (Figure 8b). The composition of the rocks is similar to high-alumina olivine tholeiites of the Cascade Range, which reflect basaltic volcanism under extensional conditions through lithosphere with a previous history of subduction volcanism [*Bacon et al.*, 1997]. The intrusive rocks thermally metamorphose adjacent argillaceous and limestone country rocks. Similar diabasic rocks in the Philip Smith Mountains quadrangle about 60 km east of the TACT transect yielded a conventional K-Ar plagioclase age of 363±11 Ma (Late Devonian) [*Brosgé et al.*, 1979a].

The Upper Devonian (Frasnian) Beaucoup Formation was defined by *Dutro et al.* [1979] in the southeastern Philip Smith Mountains quadrangle as about 545 m of clastic and carbonate rock and unmeasured units of conglomerate and phyllite stratigraphically beneath the Hunt Fork Shale and above the Skajit Limestone. *Dillon et al.* [1988] and *Dillon* [1989] extended the Beaucoup into the area of the TACT transect based primarily on the age and lithologic similarity of the Upper Devonian metalimestone bodies of the Beaucoup type section to those at the base of the Dietrich River phyllite. The Beaucoup of *Dillon et al* [1988] and *Dillon* [1989] included some of the volcaniclastic rocks in the Nutirwik Creek, as well as fine-grained metaclastic rocks of the Dietrich River phyllite. Elsewhere, however, most of the Dietrich River phyllite was assigned to the Hunt Fork Shale, and most of the Nutirwik Creek was assigned to a "Whiteface Mountain unit" thought to be equivalent to the Beaucoup [*Dillon et al.*, 1988]. Our investigation indicates that the Dietrich River phyllite and Nutirwik Creek metavolcaniclastic rocks are structurally distinct units of different, but overlapping, age and contrasting composition that should not be combined into a single unit. Whether the carbonate rocks near the base of the Dietrich River phyllite are correlatives of the limestones of the Beaucoup Formation is presently unclear. Limestones in the type section of the Beaucoup Formation are interbedded with coarser grained clastic rocks (sandstone and conglomerate) [*Dutro et al.,* 1979] than those of the Dietrich River phyllite and hence may be a different unit or facies.

Likewise, the fine-grained metaclastic rocks of the Dietrich River phyllite are distinct from the Hunt Fork Shale because in contrast with the Dietrich River phyllite, the Hunt Fork is generally coarser grained (siltstone and fine-grained sandstone) and thicker bedded, has a significantly higher sandstone-to-shale ratio, and lacks abundant mafic intrusive rocks. The composition of its clastic units and known age relations suggest that the Dietrich River unit is either stratigraphically lower than or a distal equivalent of the Hunt Fork Shale. Although the Dietrich River unit may have been part of the same depositional system as the Hunt Fork, it is presently structurally detached.

Metaclastic rocks forming the southern flank of the Snowden Creek synform are generally less distinct than those on the northern flank of the synform. Of these, only the Snowden Creek phyllite (unit of *Dumoulin and Harris* [1994]) can be correlated reliably across the Snowden Creek synform (Figure 3b). Underlying the Snowden Creek phyllite is the Vi Creek schist, which consists of light gray, laminated, very fine grained white mica-chlorite-quartz schist (Table 3). A sedimentary protolith for this schist is indicated by layers of (1) sparse metaconglomerate, (2) coarse relict grains of plagioclase and quartz, whose angular to euhedral shapes suggest a tuffaceous origin, and (3) isolated marble and calcareous schist. The age of the Vi Creek is constrained only by a single conodont fragment, dated Ordovician to Triassic (A.G. Harris, unpublished data, 1990), from a marble body within the unit. The Vi Creek schist grades southward into the Hammond River phyllonite.

The Hammond River phyllonite is distinguished from the Vi Creek schist by its highly pervasive foliation and friable character. This unit consists of phyllonite and local mylonite that comprise lenses and zones compositionally similar to the adjacent Vi Creek schist, and the Midnight Dome schist of the Coldfoot terrane. The Hammond River phyllonite contains large, isolated, ridge-capping lenses of very fine grained, black quartzite that are probably tectonic. No fossils have been found in the Hammond River phyllonite, although the black quartzite lenses were previously correlated with Silurian and Ordovician rocks in the Mount Doonerak antiform [*Dillon et al.,* 1986].

Coldfoot Terrane

The Coldfoot terrane consists of intensely deformed metamorphic rocks that lie south of the Hammond terrane in the southern part of the metamorphic core of the Brooks Range (Figure 1). Rocks of the Coldfoot terrane are primarily thoroughly recrystallized quartz-rich schists that retain few or no primary textural features. Typically these rocks display greenschist-facies metamorphic assemblages but locally retain relict minerals and pseudomorphs of an earlier phase of high-pressure metamorphism [*Dusel-Bacon et al.,* 1989]. From north to south along the TACT transect, we divide the Coldfoot terrane into five informally named units and an unnamed grouping of orthogneiss plutons (Figure 3b and Table 4).

North of the Wiseman thrust fault (Figure 3b), the Coldfoot terrane is divided into the Midnight Dome schist, consisting of quartz-rich schist, quartzite, and minor mafic schist and marble, and the overlying Nugget Creek greenschist, a mafic schist unit. The Blue Cloud Mountain schist is a fine-grained mafic schist that may be a mylonitic body related to the Nugget Creek greenschist. The Nugget Creek greenschist is commonly crowded with pseudomorphs of very fine grained chlorite and albite± actinolite after amphibole. Pseudomorphs after amphibole, rarely with cores of a blue amphibole (Figure 13), are also present in metabasite and quartzite layers in the Midnight Dome schist, suggesting a shared, high pressure metamorphic history.

Chemical analyses of mafic schist from the Midnight Dome and Nugget Creek are basaltic and similar to normal mid-oceanic ridge basalts (NMORB) on elemental-abundance diagrams (Figure 8c). The patterns for these mafic schists are also similar to the mafic

Table 4. Stratigraphic Data for Coldfoot Terrane in TACT Study Area, Central Brooks Range.

Unit	Lithology	Protolith	Age
Nugget Creek greenschist	mafic schist (chl-wm-qz-ab) with late albite porphyroblasts; contains pseudomorphs of amphibole	mafic volcanic rocks	pre-Cretaceous protolith, probably Devonian or older
Midnight Dome schist	light gray quartz schist (qz-wm) and structurally higher unit of micaceous quartzite, calcareous schist, and marble; contains intercalated layers of mafic schist that become more numerous upward; contains pseudomorphs of amphibole, rarely cored by blue amphibole	silica-rich pelite, siliceous tuff, or chert	pre-Cretaceous protolith, probably Devonian or older; metamorphic white mica yielded Early Cretaceous Ar-Ar age (130 to 120 Ma)(1)
Blue Cloud Mountain schist	fine-grained, mylonitic(?) mafic schist (chl-wm-qz-gnt-ab) with abundant late albite porphyroblasts	mafic volcanic rocks	pre-Cretaceous protolith, probably Devonian or older
Marion Creek schist	interlayered medium-grained quartzite and graphitic pelitic and semipelitic schist (qz-chl-wm-ep±chltd±gnt) with lenses of mafic schist (chl-gam-ep-ab)	continentally derived organic-rich pelitic deposits with interlayered felsic and mafic volcanic rocks and rare ultramafic rocks	Devonian to Cretaceous protolith; contains detrital zircons that yield Precambrian and Late Devonian (370 to 360 Ma) U-Pb ages(2); metamorphic white mica yielded Early Cretaceous Ar-Ar age (130 to 120 Ma)(1)
Orthogneiss plutons	moderately to strongly foliated bt±wm±hb±gnt orthogneiss intrudes Emma Creek schist	bt±hb±gnt quartz monzonite	Early to Middle Devonian U-Pb ages (393 to 391 and 398 to 381 Ma)(3)
Emma Creek schist	calcareous schist (cc-chl-wm-qz±ab±ep) with subordinate interlayered noncalcareous schist (qz-chl-wm) and marble	continentally derived calcareous pelitic deposits and sparse limestone	Silurian to Devonian protolith; at least locally early Early Devonian (Lochkovian) protolith(2)

Sources are 1, *Blythe et al.* [1996]; 2, *Moore et al.* [this issue]; 3, *Aleinikoff et al.* [1993]. Abbreviations are ab, albite; bt, biotite; cc, calcite; chl, chlorite; chltd, chloritoid; ep, epidote; gam, green amphibole; gnt, garnet; hb, hornblende; qz, quartz; wm, white mica.

hypabyssal rocks of the Dietrich River phyllite in the Hammond terrane (Figure 8b), although they lack the obvious negative Ta anomaly observed in the Dietrich River data.

The Coldfoot terrane south of the Wiseman thrust is divided into two units, the Emma Creek schist and the Marion Creek schist. The structurally higher unit is the Marion Creek schist, which consists of quartz- and mica-rich schists that are characteristic of the Coldfoot terrane and were described east of the TACT transect by *Gottschalk* [1990]. The Marion Creek contains sparse, lenticular units of mafic schist that have basaltic and ultramafic compositions. Elemental-abundance diagrams for the metabasalt lenses indicate that they are enriched in LIL elements and suggest affinity with enriched mid-oceanic ridge basalts (EMORB) (Figure 8e). Analysis of single-grain U-Pb ages of detrital zircons in a quartzite from the Marion Creek schist shows that the protolith source area contained rounded Precambrian (3.0, 2.0 to 1.8, and 1.5 to 1.4 Ga) and euhedral Late Devonian (370 to 360 Ma) zircons [*Moore et al.,* this issue]. The youngest zircons indicate that the maximum age of the protolith of the Marion Creek schist is Late Devonian.

Pseudomorphs of white mica + epidote after lawsonite, albite + chlorite ± quartz after glaucophane, and eclogitic metabasite near Coldfoot indicate that older blueschist-facies assemblages were once present in the Marion Creek schist [*Gottschalk*, 1990; *Till and Moore,* 1991]. Maximum metamorphic conditions are estimated to have been 375° to 400°C and 9 to 12 kbar [*Gottschalk and Oldow,* 1988; *Gottschalk,* 1990]. The high-pressure assemblages were overprinted by pervasive upper greenschist-facies assemblages formed at similar temperatures but lower pressures of 3 to 6 kbar [*Gottschalk and Oldow,* 1988].

The Emma Creek schist underlies the Marion Creek schist along a contact that could be a metamorphosed fault or an unconformity [*Moore et al.,* this issue] (Figure 3b). The Emma Creek schist consists principally of calcareous schist with sparse layers and lenses of marble up to 20 m thick. Conodonts indicate that the age of the protolith of the schist is Silurian or Devonian and at least locally early Early Devonian [*Moore et al.,* this issue].

Near the Dalton Highway, the Emma Creek schist is intruded by a strongly foliated muscovite-biotite quartz monzonite orthogneiss (Figure 3b), whose intrusive origin is indicated by calc-silicate rocks (tactite) along its margin. East of the TACT study area, larger bodies of orthogneiss (Horace Mountain and Geroe Creek plutons of *Aleinikoff et al.* [1993]) intrude calcareous rocks lithologically similar to those in the Emma Creek schist (Figure 1). One body of orthogneiss in the same area (Twin Lakes pluton of *Aleinikoff et al*. [1993]) (Figure 1), however, intrudes amphibolitic metabasite that is structurally below the Marion Creek schist but is in uncertain contact with the Emma Creek schist [*Brosgé and Reiser,* 1964] (T.E. Moore, unpublished data, 1990). Zircons from hornblende-biotite orthogneisses (the Horace Mountain and Geroe Creek plutons) yield nearly concordant U-Pb ages of 393 to 391 Ma (Early Devonian), whereas zircons from two-mica orthogneisses (the Twin Lakes pluton and the body near the Dalton Highway that intrudes the Emma Creek schist) are discordant but suggest crystallization between 398 to 381 Ma (Early to Middle Devonian) [*Aleinikoff et al.,* 1993]. Chemical analyses indicate that the orthogneisses are mostly metaluminous, and elemental-abundance diagrams display similar patterns that are enriched in LIL elements with prominent negative Ta-Nb, Sr, P, and Ti anomalies (Figure 11b). The negative Ta-Nb anomalies may be indicative of crystallization from a dominantly subduction-generated magma or, alternatively, may be the result of mixing of some other magma type with partial melts that were derived from pre-existing subduction-related rocks in the lower crust (C.R. Bacon, unpublished data, 1996). Elemental-abundance diagrams for the amphibolitic metabasite country rocks of the Twin Lakes body display prominent Ta anomalies and patterns similar to those of island arc basalts (Figure 8d). If the amphibolitic metabasalt is cogenetic with the Twin Lakes orthogneiss body, these data support the contention of *Rubin et al.* [1990] that the belt of orthogneiss plutons in the Coldfoot terrane represents part of an extensive Devonian continental arc. However, the protolith age of the amphibolite is unknown and may be substantially older than the intruding orthogneiss. Metamorphic conditions for the orthogneiss bodies were estimated at 370° to 395°C and 7 to 9.8 kbar [*Patrick,* 1995].

Slate Creek Terrane

The Slate Creek terrane is a narrow, south dipping enigmatic package of rocks that lies between the Coldfoot terrane to the north and the Angayucham terrane to the south (Figures 1 and 2). We have divided this terrane into three informal units: a northern Slate Creek phyllonite, a central Rosie Creek sandstone, and a southern, unnamed unit of tectonic mélange (Figures 3b and 14).

On the north, the Slate Creek phyllonite is in gradational contact with the Marion Creek schist of the Coldfoot terrane. Within this transitional zone, layers and phacoids of medium-grained quartz-mica schist identical to the Marion Creek schist are interlayered with zones of gray, fine- to very fine grained, intensely foliated quartz-chlorite-white mica schist. Southward in the Slate Creek unit, the layers and phacoids of coarser grained schist diminish in abundance and size, and the finer grained, intensely foliated zones become dominant. Farther south, the rocks take on a phyllitic appearance and in thin section consist of sand-sized, frayed grains of quartz and elongate grains of coarse pennine chlorite in an intensely foliated, comminuted matrix of quartz, chlorite, white mica, and minor albite. Much of the Slate Creek has the appearance of a cataclastically deformed sandstone as described by *Dillon* [1989], but the northern gradational contact and similar appearance of coarse pennine chlorite in the Slate Creek phyllonite to chlorite in the Marion Creek schist indicate that most or all of the Slate Creek consists of phyllonite and mylonite derived from the Marion Creek schist. We conclude that the Slate Creek phyllonite was derived from intense shearing in a strain gradient developed in the Marion Creek schist.

Sparse lenses of metabasite are present in the Slate Creek phyllonite and commonly retain metamorphic mineral assemblages and near-static textures similar to metabasite lenses in the Marion Creek schist. One metabasite lense in the Slate Creek south of Coldfoot retains crossite, whereas another has pumpellyite-actinolite facies assemblages [*Gottschalk and Oldow,* 1988]. We conclude that these metabasites acted more competently than other lithologies in the Slate Creek phyllonite, which deformed around the lenses during deformation. In support of our interpretation that the Slate Creek metabasites were derived from those in the Marion Creek schist , Slate Creek metabasites display light-rare-earth-element (LREE)-enriched patterns on elemental-abundance diagrams that are generally similar to EMORB and to patterns of metabasites in the Marion Creek schist (Figures 8h and 8e). An exception to this is a lense of mostly serpentinized dunite or troctolite southeast of Coldfoot that retains igneous rather than metamorphic features, including poikilitic clinopyroxene and relict heteradcumulate textures. Ultramafic metabasites in the Marion Creek schist are composed largely of mats of actinolite and chlorite and lack well-preserved igneous textures.

The Rosie Creek sandstone (Rosie Creek allochthon of *Oldow et al.* [1987]) consists of medium- to fine-grained chert- and quartz-rich sandstone, as well as subordinate interlayered argillite. The sandstone displays abundant planar lamination, flute casts, and local small-scale trough cross-stratification; hummocky cross-bedding is reported in the unit by *Gottschalk* [1987]. Interbedded argillite has yielded late Early Devonian palynomorphs [*Gottschalk*, 1987]. Although correlated with the Hammond terrane [*Oldow et al.,* 1987], the unit has closer compositional and textural similarities to Upper Devonian sandstones of the Endicott Group in the younger Endicott Mountains allochthon [*Murphy and Patton*, 1988]. Compositionally similar clastic units are also present in the North Slope terrane, including (1) local basinal deposits of the Middle Devonian Ulungarat Formation of *Anderson et al.* [1994] and (2) Lower(?) and Middle Devonian chert arenite in the Topogoruk well [*Collins,* 1958], both of which are nearly equivalent in age to the Rosie Creek.

The unnamed southern belt of the Slate Creek terrane is a tectonic mélange consisting of blocks and lenses of mafic volcanic rocks, diabase, chert, and chert arenite in a poorly exposed matrix of sheared sandstone and black shale. The volcanic rocks retain igneous textures, fresh clinopyroxene, and locally display pillow structures. Geochemical data from these blocks indicate enrichment in LIL elements relative to NMORB and display patterns similar to, but with partly higher values than, EMORB basalts and basalts of the adjacent Angayucham terrane (Figures 8g and 8f). The chert blocks are typically well bedded and yield Mississippian and Triassic to Early Jurassic radiolarians similar to those in the Angayucham terrane [*Jones et al.*, 1988]. The absence of dynamothermal metamorphic mineral assemblages and the presence of tectonic breccia suggest that the southern belt is a mélange derived by brittle deformation of the adjacent Angayucham terrane and the chert-quartz arenite of the Rosie Creek sandstone.

The nature of the Slate Creek terrane along the TACT transect has been the subject of some controversy. *Murphy and Patton* [1988] and *Karl and Mull* [1993] interpreted much of the unit as a variably deformed sedimentary unit, whereas *Gottschalk and Oldow* [1988] and *Dillon* [1989] interpreted the Slate Creek phyllonite as part of the Coldfoot terrane (schist belt). Our observations indicate that the entire terrane is a complex mélange consisting to the north of a ductile shear zone with a southward increasing strain gradient (Slate Creek phyllonite) and to the south of a tectonic mélange developed under brittle conditions (unnamed southern belt). The intervening Rosie Creek sandstone pinches out to the east between the adjacent units (Figure 3b), suggesting that it is a map-scale fault sliver between the two tectonic units. Although mostly covered, the northern margin of the Rosie Creek sandstone appears to be sharply juxtaposed against the Slate Creek phyllonite, as described by *Gottschalk and Oldow* [1988]. This contact (their Rosie Creek fault) suggests that the ductile shearing to the north is relatively older than the brittle deformation present in the southern part of the terrane.

Angayucham Terrane

Regionally, the Angayucham terrane consists of two subunits, a structurally higher unit of ultramafic rocks and mafic plutonic rocks and a structurally lower unit of mafic volcanic rocks, chert, and diabase [*Moore et al.*, 1994a]. Along the TACT transect, only south dipping exposures of the structurally lower unit are present (Figures 3b and 14). The upper unit may be covered by Cretaceous sedimentary rocks of the Koyukuk Basin to the south [*Dillon,* 1989]; however, gravity and magnetic data do not support the presence of ultramafic rocks in this part of the Koyukuk Basin [*Cady*, 1989].

Along the TACT route, the lower unit of the Angayucham terrane consists of structurally interleaved bodies of clinopyroxene-plagioclase-phyric pillow basalt, breccia, massive basalt, and diabase; minor gabbro and bedded units of radiolarian chert and argillite; and sparse lenses of limestone, silicified limestone, basaltic graywacke, and tuff. The chert is black, gray, green, maroon, and brown and locally is intruded by diabase dikes and sills. Radiolarians from the chert units and interpillow chert indicate that the Angayucham includes strata of Devonian, Mississippian, Late Mississippian(?) to Early Pennsylvanian, Middle Pennsylvanian to Early Permian, Early Permian, and Triassic to Early Jurassic age [*Jones et al,* 1988] (B. Murchey, unpublished data, 1996). The basaltic rocks and diabase have patterns slightly enriched in LIL elements relative to NMORB and are similar to EMORB on elemental-abundance diagrams (Figure 8f). These data confirm the results of an earlier geochemical study on these rocks by *Barker et al.* [1988]. The mafic rocks contain static metamorphic assemblages that range from prehnite-pumpellyite to plagioclase amphibolite facies. These are low-pressure assemblages that likely formed by ocean floor metamorphic processes that accompanied or followed eruption [e.g., *Harper et al,* 1988].

The rocks of the Angayucham terrane along the TACT route have been interpreted as a south dipping imbricate stack of oceanic platform and seamount basaltic rocks and overlying pelagic sedimentary rocks that were structurally assembled in a subduction zone [*Barker et al.,* 1988; *Dillon,* 1989]. The fossil ages suggest pelagic deposition was continuous for almost 200 m.y.; the absence of continental detritus in the deposits suggests that deposition occurred away from continental land masses. Contacts between the imbricates are zones of breccia and mylonite commonly marked by lenses of chert.

Structural Relations

Autochthon, Parautochthon, and Foreland Basin

Rocks of the North Slope terrane constitute the autochthon and parautochthon of the Brooks Range orogen and display a regional northwesterly dip in the northern part of the study area. This dip reflects their northerly trend along the margin of the northeastern salient of the Brooks Range and provides a down plunge view of the crustal structure of the parautochthon and overlying foreland basin strata of the Colville Basin.

Parautochthonous rocks in the TACT transect display a fold-and-thrust-belt structural style. The dominant structure in these rocks is the broad, southwest plunging Ribdon River anticlinorium in the northeastern corner of the study area (Figures 2 and 3a). This structure is about 15 km across and is similar to other anticlinoria in the northeastern salient of the Brooks Range outside the study area. Although pre-Mississippian rocks are not exposed in the study area, the anticlinorium likely reflects a duplex at depth in pre-Mississippian rocks, such as those described elsewhere in the northeastern Brooks Range [*Wallace and Hanks,* 1990; *Wallace,* 1993]. The anticlinorium is interpreted to mark north transported, fault-bend-folded horses in a duplex with a floor thrust at depth in pre-Mississippian rocks and a roof thrust in the overlying Kayak Shale [*Wallace*, 1993].

Carbonate rocks in the Lisburne Group of the Ellesmerian sequence comprise small folds parasitic to the Ribdon River anticlinorium (Figure 15a). The small folds are controlled principally by the thick, incompetent shale of the Echooka Formation (Sadlerochit Group) and the Kayak Shale above and below, respectively, the more structurally competent carbonate rocks of the Lisburne Group. This style of deformation is described in more detail by *Wallace et al.* [this issue] and is equivalent to the detachment folds farther north [*Wallace and Hanks*, 1990;*Wallace*, 1993].

Strata above the Echooka Formation are also in normal stratigraphic order in most areas. Although poorly exposed, sandstone of the Ivishak Formation and the Kingak Shale can be traced southwestward along the mountain front in sparse exposures to apparent abrupt terminations, probably against Cretaceous strata of the Okpikruak and Fortress Mountain Formations north of Elusive Lake (Figures 2 and 3a). The apparent truncations are suggestive of a cryptic, northeast trending fault (dotted structure northwest of Elusive Lake in Figure 3a) that cuts up section through the upper part of the Ellesmerian sequence on the northern flank of the Ribdon River antiform and probably into the Torok Shale outside the TACT study area. To the southwest in Atigun Gorge, a well-exposed, north dipping fault, which places the lower part of the Fortress Mountain Formation of the Colville Basin onto rocks of the Endicott Mountains allochthon and De Long Mountains terrane, may be a back thrust, which we call the Atigun Gorge back thrust [*Mull et al.,* this issue]. The eastward extension of this fault has not been identified in the poorly exposed areas northeast of Atigun Gorge, but it likely bounds the base of the Fortress Mountain Formation and may merge northeastward with the cryptic fault that truncates the Ellesmerian section north of Elusive Lake (Figures 2 and 3a). If this is the case, the combined structure may be interpreted as a roof thrust of a west plunging triangle zone above the De Long Mountains terrane, Endicott Mountains allochthon, and part of the North Slope terrane. The Atigun Gorge back thrust is probably also the detachment surface above which broad folds developed in the Fortress Mountain Formation and Nanushuk Group at Atigun and Marmot synclines, respectively (Figures 2 and 3a). Fission track data are consistent with field evidence that deformation north of the range front is post-Albian and suggest that shortening in this area is related to formation of the northeastern Brooks Range during the Tertiary [*O'Sullivan et al.,* 1993a, b, this issue; *Blythe et al.,* 1996; *O'Sullivan,* 1996].

It has been suggested that the northeastern salient of the Brooks Range is bounded on its northwestern margin along the mountain front by a left-lateral strike-slip fault (the Canning displacement zone of *Grantz and May* [1983]). Although a steeply northwest dipping slaty cleavage is present along the mountain front in our study area, no strike-slip fault is evident, and Ellesmerian and Brookian strata are in normal stratigraphic order. The large structural relief of the uplifted basement rocks northeast of our study area relative to the Albian strata of the Colville Basin along the TACT transect is best explained by an oblique ramp that bounds the duplexes developed in pre-Mississippian rocks as outlined above.

Endicott Mountains and Higher Allochthons

The Endicott Mountains allochthon occupies a broad synformal low in the Endicott Mountains north of the Mount Doonerak antiform. The stratigraphic succession in this area is considered allochthonous because it has a faulted base and differs from the North Slope terrane rocks exposed in the northeastern Brooks Range to the north and from the Mount Doonerak antiform to the south [*Dutro et al.,* 1976; *Mull,* 1982; *Mull et al.,* 1987b) (Figure 7). An allochthonous interpretation for the Endicott Mountains succession has been used in most published cross sections [e.g., *Mull et al.,* 1987a; *Oldow et al.,* 1987; *Grantz et al.,* 1991; *Moore et al.,* 1994a; *Blythe et al.,* 1996]; however, *Kelley and Brosgé* [1995] recently argued that this succession need not constitute a far-travelled thrust sheet. They instead proposed a balanced model that interprets the Endicott Mountains succession as deformed and inverted in situ basinal deposits related to Mississippian basins in the North Slope subsurface. We disagree with the interpretation of *Kelley and Brosgé* [1995] because (1) the stratigraphic succession in the Mount Doonerak antiform displays close stratigraphic affinity to strata of the North Slope terrane, an unexpected relation for rocks deposited on opposite sides of a large basin; (2) the Endicott Mountains succession is of continental-margin proportions, dimensions at least 4 times larger than the largest of the local subsurface Mississippian basins of the North Slope [e.g., *Brosgé et al.,* 1988, Figure 14]; (3) clastic deposits of the Endicott Mountains succession are primarily or entirely Late Devonian, whereas the clastic deposits in the North Slope basins are entirely Mississippian where penetrated by wells or exposed [*Kirschner and Rycerski*, 1988]; (4) facies and clast-size distributions and paleocurrent data from Devonian, Carboniferous, Permian, and Triassic strata in the Endicott Mountains succession show that regional depositional dip was inclined southwestward and provide no evidence of a southern source area in the Mount Doonerak area nor any evidence of radial drainage toward a subsiding basin low in the north central Brooks Range [e.g., *Moore et al.,* 1989, 1994a; *Adams et al.*, this issue]; (5) the Endicott Mountains succession demonstrably rests in structural contact on younger rocks along the northern flank of the Mount Doonerak antiform, relations that are not accounted for by *Kelley and Brosgé* [1995, Figures 9e and 9f]; (6) northward transported lower Paleozoic rocks, including the Ordovician to Devonian and possibly older Skajit Limestone, are restored to stratigraphic positions above Cambrian to Silurian rocks of the Mount Doonerak antiform [*Kelley and Brosgé*, 1995, Figure 9a], an improbable restoration given the overlapping ages of the rocks; (7) the "carbonate ramp" in the Lisburne Group, used by *Kelly and Brosgé* [1995, Figure 6] to constrain the amount of displacement at the base of the Endicott Mountains allochthon to a few kilometers, reflects shortening across the Toyuk thrust system rather than a stratigraphically controlled facies change [*Dumoulin et al.,* this issue]; and (8) regionally, the continental-margin Endicott Mountains succession is structurally overlain by far-displaced rocks, including ophiolite [*Roeder and Mull,* 1978], that indicate large amounts of northward displacement are geologically reasonable. Although in situ basin restorations, such as the one discussed by *Kelley and Brosgé* [1995], are geometrically possible, we instead subscribe to the interpretation that the Endicott Mountains allochthon has been thrust northward at least 90 km from an original position south of the Mount Doonerak area as discussed by *Mull et al.* [1987b].

Rocks of the Endicott Mountains allochthon form an east-west trending fold-and-thrust belt along the northern margin of the main axis of the Brooks Range. As in the Ellesmerian sequence of the North Slope terrane, deformation of the Endicott Mountains succession is stratigraphically controlled by incompetent shale-rich units interlayered with more competent units (Figure 15b). Major detachment surfaces are present in the Upper Devonian Hunt Fork Shale, the Mississippian Kayak Shale, and the Permian Siksikpuk Formation of the Etivluk Group. Thrust-truncated detachment folds are developed in intervening competent units of the Upper Devonian Noatak Sandstone, Upper Devonian and Lower Mississippian(?) Kanayut Conglomerate, and the Mississippian to Pennsylvanian Lisburne Group. Each competent unit is structurally thickened in duplexes that are largely isolated, or compartmentalized, by roof and floor thrusts in the incompetent shale-rich units. The Permian to Lower Cretaceous rocks in the upper part of the allochthon consist of thin-bedded shale-rich units that are deformed by abundant close-spaced thrust faults and small-scale folds that locally resemble broken formation or mélange. The resulting stacked series of internally deformed units (multistoried duplexes) in the allochthon are tilted gently northward, such that units retain overall normal stratigraphic order from oldest in the south to youngest in the north. This style of deformation is shown schematically in Figure 15b and is the subject of an accompanying paper [*Wallace et al.,* this issue].

Thrust faults locally breach the roof thrusts of the stacked duplexes. The most significant of these is the Toyuk thrust system [*Porter,* 1966], which consists of a system of faults that can be traced to the west for nearly 250 km where they intersect the northern Brooks Range mountain front. The eastern extent of the thrust system is unknown. The Toyuk places the Hunt Fork Shale onto the Kayak Shale for most of its length and locally onto the Lisburne Group in the TACT transect (Figure 3a). The juxtaposition of unlike facies in the Endicott and Lisburne Groups and Siksikpuk Formation (Figure 9 and Table 2) and the great extent of the Toyuk suggest a large amount of shortening on this fault regionally. A minimum of 8 km of northward displacement on the thrust was reported by *Kelley and Brosgé* [1995], and a minimum of 18 km of displacement can be documented near its westernmost extent in the Killik River quadrangle [*Mull et al.,* 1994]. Structural relations may indicate a smaller amount of displacement in the TACT study area [*Wallace et al.,* this issue], although still sufficient enough to juxtapose the unlike facies.

Along the southern margin of the Endicott Mountains allochthon, the base of the allochthon is placed at the detachment surface underlying the Hunt Fork Shale. Within this region, a strain gradient progresses from near isoclinal folds near the basal thrust to asymmetric folds higher in the Hunt Fork [*Handschy and Oldow,* 1989]. Although the detachment at the base of the Hunt Fork is a convenient feature for delimiting the base of the allochthon, the basal thrust probably steps down to the Amawk thrust [*Mull et al.,* 1987b] below a thin sliver of Hammond terrane rocks that underlies the Hunt Fork Shale on the northern limb of the Mount Doonerak antiform (Figure 16). This relation implies that the basal thrust cuts down section to the south beneath the Hammond terrane.

Along the northeastern margin of the contiguous Endicott Mountains allochthon (Figure 2 between measured sections A-B and C), the base of the allochthon is within a zone of gently south dipping thrust sheets of Lisburne Group carbonate rocks. The position of the basal thrust at the northern contiguous margin is constrained by the contrasting facies of the Permian Echooka Formation of the North Slope parautochthon north of the thrust and coeval strata of the Siksikpuk Formation of the Endicott Mountains allochthon south of the thrust, as explained under "Endicott Mountains Allochthon" above (Figure 6). The deformational style in the parautochthon beneath the allochthon is similar to that in the allochthon (Figure 15b) and differs from the style of the parauthochthon in the northeastern Brooks Range (Figure 15a) (see "Autochthon, Parautochthon, and Foreland Basin" above), probably because coeval units with nearly equivalent mechanical stratigraphy are juxtaposed across the base of the allochthon [*Wallace et al.,* this issue].

The transition from Hunt Fork Shale at the base of the Endicott Mountains allochthon in the south to Lisburne Group along the northeastern margin of the contiguous allochthon indicates that progressively younger rocks form the base of the allochthon northward. This observation requires that the basal thrust of the allochthon climbs up section to the north in the hanging wall. The basal thrust is underlain by the Permian Echooka Formation of the North Slope terrane in the northern and southern parts of the contiguous allochthon (Figure 3a), although the basal thrust is locally underlain by Triassic rocks west of the TACT study area in the Mount Doonerak antiform. This relation suggests that for most of its distance across the northern Brooks Range, the allochthon glided on a detachment developed near the top of the Echooka Formation or in the Shublik Formation. Nowhere in the contiguous allochthon have Jurassic or Cretaceous rocks been observed beneath the basal contact (Figure 3), bringing question to bear on most published tectonic models which show Cretaceous deposits thrust beneath the Endicott Mountains allochthon at least as far south as the Toyuk thrust system.

At the mountain front at Atigun Gorge, the Endicott Mountains allochthon consists of complexly folded and thrust-faulted Permian to Lower Cretaceous thin-bedded, shale-rich rocks that commonly form broken formation and mélange. These rocks are structurally overlain by similarly deformed Triassic and Jurassic chert, and Lower Cretaceous synorogenic deposits of the Okpikruak Formation, which together constitute the higher allochthon [*Mull et al.*, this issue] assigned here to the De Long Mountains terrane. This higher allochthon lies beneath the Atigun Gorge back thrust, which displaced the Colville Basin deposits southward over the allochthonous rocks (Figure 3a). Although poorly exposed and in isolated outcrops, the mélange and broken formation of the De Long Mountains terrane and Endicott Mountains allochthon can be traced northeastward along the mountain front to near Elusive Lake, where they pinch out between underlying rocks of the North Slope terrane and overlying Colville Basin deposits and indicate the approximate northernmost extent of the allochthonous rocks (Figures 2 and 3a). Rocks of the Endicott Mountains allochthon in the Elusive Lake area are restricted to the Lower Cretaceous coquinoid limestone and shale unit, suggesting that the basal thrust of the allochthon cuts up section in the hanging wall to a detachment in Jurassic or Lower Cretaceous strata near the northern limit of the allochthon. The coquinoid limestone and shale unit is probably too thin and incompetent to have been displaced by itself. However, if the De Long Mountains terrane were first thrust over the Endicott Mountains allochthon, the additional thickness would have provided sufficient strength for both allochthons to be emplaced together. South and west of Elusive Lake, the Permian Echooka and Triassic Shublik Formations, respectively, of the North Slope terrane are in the footwall below the allochthonous rocks, indicating that the Endicott Mountains allochthon glided on a detachment in Permian and Triassic strata. The absence of Jurassic and Cretaceous strata in the footwall beneath the Endicott Mountains allochthon near its leading edge, and the conformable parautochthonous Mississippian to Lower Cretaceous stratigraphic succession on the northern flank of the Ribdon River anticlinorium (Figure 3a), suggest that the allochthons terminated in a triangle zone beneath the Jurassic and Cretaceous Kingak Shale of the North Slope terrane not far to the north of Elusive Lake.

The basal thrust of the Endicott Mountains allochthon and the overlying rocks of both the Endicott Mountains allochthon and the De Long Mountains terrane are clearly folded by the Ribdon River anticlinorium (Figure 3a), indicating that the anticlinorium is a relatively late feature. This anticlinorium suggests the possibility of a younger triangle zone whose floor thrust lies at depth in pre-Mississippian rocks of the North Slope terrane and whose roof thrust may be the Atigun Gorge back thrust.

Comparison of the great thickness of strata and high structural relief of the Endicott Mountains allochthon in the Atigun Pass area, 40 km south of the mountain front, with the much thinner strata and lower structural relief in the Atigun Gorge-Elusive Lake area shows that the Endicott Mountains allochthon constitutes a northward tapered, structurally thickened wedge. At the leading edge of the Endicott Mountains allochthon, the presence of an overlying erosional remnant of the De Long Mountains terrane suggests that the leading edge of another northward tapered wedge was emplaced onto the Endicott Mountains allochthon prior to its movement. The Atigun Gorge back thrust places Albian foreland basin rocks over both wedges, indicating that the final increment of displacement of these units occurred in post-Albian time as part of a young triangle zone that deformed the earlier formed structural stratigraphy.

Mount Doonerak Antiform

The Mount Doonerak antiform is a prominent, northeast trending, doubly plunging structural feature along the western margin of the TACT study area (Figure 1). This antiform has received considerable attention because it exposes rocks of the North Slope terrane in a structural window through rocks of the Hammond terrane and Endicott Mountains allochthon [e.g., *Mull*, 1982; *Mull et al.*, 1987b; *Oldow et al.,* 1987; *Seidensticker et al.*, 1987; *O'Sullivan et al.*, 1997]. Seismic data show that the antiform is a crustal-scale duplex that has a structural relief of about 15 km [*Levander et al.*, 1994; *Fuis et al.,* 1995] (Figure 17). Faults in the duplex root in a detachment at about 25 km depth and merge upward into a roof thrust (Blarney Creek thrust of *Seidensticker et al.* [1987]) in the Kayak Shale above the unconformity at the base of the Ellesmerian sequence [*Oldow et al.,* 1987; *Fuis et al.*, 1995]. The detachment in the Kayak Shale also serves as a floor thrust for a duplex developed in overlying carbonate rocks of the Lisburne Group (Figure 17). The roof thrust for the Lisburne duplex lies near the top of the Permian Echooka Formation in most places, but at Bombardment Creek, 10 km west of the TACT study area, the thrust is above the Triassic Shublik Formation and Karen Creek Sandstone (Figure 7). Directly above the Permian-Triassic rocks at the Amawk thrust are the Devonian Nutirwik Creek metavolcaniclastic rocks and sparse blocks of the Skajit Limestone of the Hammond terrane.

The structural style of the Mount Doonerak antiform is generally similar to that of the North Slope terrane in the northeastern Brooks Range [*Wallace and Hanks*, 1990]. In both areas, large basement-cored antiforms form duplexes with roof thrusts in the Kayak Shale and floor thrusts deep in pre-Mississippian basement rocks. Although the Lisburne Group rocks above the roof thrust in the Mount Doonerak antiform are imbricated, rather than folded as in the northeastern Brooks Range, the imbricate style is similar to that of the Lisburne Group rocks of the North Slope terrane immediately below the northern edge of the Endicott Mountains allochthon. These structural similarities, coupled with the stratigraphic similarities reviewed above, indicate that the Mount Doonerak antiform is a southern extension of parautochthonous rocks exposed in the northeastern Brooks Range.

Metamorphic Core

Rocks of the Hammond and Coldfoot terranes, the metamorphic core of the Brooks Range, display semipenetrative to penetrative fabrics and greenschist-facies mineral assemblages. The dominant foliation in the Hammond terrane along the TACT transect is a flattening foliation that overprints sedimentary layering and locally is folded into late open folds. The dominant foliation in the Coldfoot terrane, in contrast, is a transposition foliation formed by folding of an earlier foliation. As in the Hammond terrane, the dominant foliation of the Coldfoot terrane is locally folded into late open folds. Relict high-pressure mineral phases and their pseudomorphs accompany an early fabric in the Coldfoot terrane, whereas greenschist assemblages in the Coldfoot terrane appear to be static or to accompany a later, dominant foliation.

North of the Snowden Creek synform (Figure 2), the Hammond terrane displays an imbricate style of deformation, as well as a pervasive phyllitic fabric. Along its northern margin, the Hammond terrane underlies the Endicott Mountains allochthon at a structural contact herein called the Chandalar Shelf thrust (Figures 2 and 3b). A regional discordance of map-scale units along this boundary is evident from the northeasterly strike and southeasterly dip of units in the Hammond terrane when contrasted to the easterly strike and northerly dip of units in the overlying Endicott Mountains allochthon (Figure 3b). The northeast striking units in the Hammond, including the Nutirwik Creek, Trembley Creek, and Skajit, pinch out northward in Dietrich River phyllite as they approach the Endicott Mountains allochthon. Just below the base of the allochthon, the foliation of the Dietrich River phyllite is rotated northward into parallelism with the base of the allochthon (Figure 18). This configuration of units is suggestive of horses in a duplex with a roof thrust in the Dietrich River phyllite.

At Table Mountain (Figure 2), east of the Mount Doonerak antiform, a duplex of the Skajit Limestone and Nutirwik Creek metavolcaniclastic rocks is clearly evident from map patterns beneath the Chandalar Shelf thrust (Figures 3b and 18). The structural relations in this area suggest that a floor thrust lies at depth beneath the Skajit and a roof thrust above the Nutirwik Creek. The fault exposed at the base of the duplex, the Table Mountain thrust, was previously interpreted as the basal thrust of the "Skajit allochthon" of *Oldow et al.* [1987], which was interpreted to place rocks of the Hammond terrane onto the Endicott Mountains allochthon. We instead interpret the Table Mountain fault as a breaching thrust that truncates the duplex of Skajit and Nutirwik Creek rocks and places it onto the Dietrich River phyllite (Figures 3b and 18). Although the duplex is well developed at Table Mountain, the Skajit pinches out southwestward away from the duplex. The pinch-out probably reflects (1) thrusts, such as the Table Mountain thrust, that ramp upward in the duplex and (2) stratigraphic or preexisting structural pinch-outs of the unit prior to deformation. A second duplex of Skajit Limestone is present in the area east of Snowden Mountain (Figure 2). As at Table Mountain, the Skajit pinches out laterally but is imbricated with thin slivers of Dietrich River phyllite (too thin to be shown in Figure 3b) instead of Nutirwik Creek metavolcaniclastic rocks.

An important relation along the northern margin of the Hammond terrane is its location beneath the Endicott Mountains allochthon and above the Amawk thrust at the northern margin of the Mount Doonerak antiform [*Dillon et al.*, 1986] (Figures 16 and 17). The Hammond terrane in this area is only about 200 m thick and is substantially thinner on the northern flank of the antiform than on the southern flank (Figure 17). The northward thinning provides evidence that the Hammond wedges out to the north beneath the Endicott Mountains allochthon.

Imbrication in the northern part of the Hammond gives way to fold-dominated deformation in the southern part of the terrane. Recumbent folds are clearly evident from the Dalton Highway in mountainside exposures of the Skajit at Sukakpak and Dillon Mountains (Figures 2 and 19). Map-scale, sheared-out hinges of Skajit appear to float in calcareous schist east of these mountains (Figure 3b). Primary layering, sparse in the Vi Creek schist, is complexly folded. The northern boundary of the folded rocks is approximately along the northern limit of the Vi Creek schist and continues eastward parallel to the trend of the Snowden Creek synform through an apparently continuous exposure of the Skajit into the Dusty Mountain phyllite (Figure 3b). West of the Dalton Highway, the folded rocks are beneath the imbricated units of the Snowden Creek, Dusty Mountain, and Jesse Mountain phyllites on a north dipping contact; however, east of the highway the opposite relation is present (Figure 3b). The cause of the change in orientation and structural stacking across the highway is uncertain, but it may be caused in part by different levels of exposure across a high-angle fault along the western margin of the Skajit in this area.

The boundary between the Hammond and Coldfoot terranes west of the TACT transect is defined by (1) high-pressure metamorphic phases in the Coldfoot terrane and (2) relict sedimentary structures in the Vi Creek schist of the Hammond terrane. These features show the substantially different metamorphic and structural histories of the two terranes. On this basis, the boundary in the western part of the transect is in the Hammond River phyllonite (Figures 3b and 20). The phyllonite contains microlithons of the adjacent Midnight Dome and Vi Creek schists. The texture and orientation of the Hammond River phyllonite suggest that it represents a ductile fault zone that dips northward beneath the

Hammond terrane. The sense of shear in the Hammond River phyllonite has not been determined. Although units directly north of the Hammond-Coldfoot boundary are undated, the older age of the Skajit in the Hammond terrane compared to the Devonian and Devonian(?) protolith age of rocks of the Coldfoot terrane below the phyllonite suggests a thrust relation. However, if the large inclusions of fine-grained, black quartzite in the phyllonite unit are tectonic fragments correlative with similar Cambrian to Ordovician lithologies in the core of the Mount Doonerak antiform, as suggested by *Dillon et al.* [1986], down-to-the-north extensional displacement may be indicated for the structure. In the eastern part of the study area, the Hammond River phyllonite is truncated by the eastward extension of the Wiseman thrust (Figures 2 and 3b).

Rocks of the metamorphic core are folded into broad antiforms and synforms that have a wavelength of 10 to 30 km. These structures include the Wiseman arch of *Gottschalk* [1987], the Mount Doonerak antiform, and the Minnie Creek Lake and Snowden Creek synforms (Figure 2). The antiforms and synforms fold all penetrative fabric elements and thus are relatively young structures. The structural relations observed at the Mount Doonerak antiform imply that the antiforms are underlain by duplexes rooted at deep crustal levels. The Minnie Creek Lake synform lies in the footwall of the Wiseman thrust, suggesting that the synform may be a footwall synform to the thrust. The Wiseman thrust of *Dillon and Reifenstuhl* [1990], located near the village of Wiseman, is a south dipping fault that is the same fault as the Minnie Creek thrust of *Oldow et al.* [1987] east of the village. West of the village, the Wiseman thrust trends west-southwest (Figure 2 and 3b), whereas the Minnie Creek continues to the west into an area where we were unable to document displacement across its mapped trace.

Transition to Hinterland

The Slate Creek and Angayucham terranes mark the southern margin of the Brooks Range orogen and its transition to the Ruby terrane and Koyukuk Basin, which together form the hinterland of the orogen. The Koyukuk Basin consists of coarse-grained mid-Cretaceous clastic rocks that, on the basis of isotopic data, are thought to overlie mafic oceanic crustal rocks related to the Angayucham terrane at depth [*Arth et al.,* 1989]. Like the Colville Basin deposits to the north, the Koyukuk Basin deposits were shed from the nascent Brooks Range orogen [*Dillon,* 1989].

The system of south dipping faults and fabrics of the Slate Creek terrane between the Coldfoot and Angayucham terranes has been interpreted to be the root zone for north transported thrusts that emplaced the Angayucham terrane onto the Arctic Alaska superterrane [e.g., *Mull, et al.,* 1987a; *Dillon,* 1989]. Other workers, however, have documented an abrupt metamorphic facies change, from low-pressure mineral assemblages in the Angayucham terrane to high-pressure assemblages in the Coldfoot terrane, that indicates at least 8 km of structural section omitted across these faults, and a down-to-the-south normal-fault relation [*Carlson,* 1985; *Gottschalk and Oldow,* 1988; *Miller and Hudson,* 1991]. *Gottschalk and Oldow* [1988] suggested that the normal faulting was the result of brittle extensional faulting along localized structures in an overall contractional regime. On the other hand, *Law et al.* [1994] and *Little et al.* [1994] presented data from structural fabrics about 35 km west of the TACT transect that suggest the normal faulting took place under ductile conditions and was the result of a regional extensional tectonic event that postdated fabric elements related to contractional deformation. In either case, displacement on the normal fault system must have been significant to drop the Angayucham terrane, the highest structural unit in the orogen, down to its position near the Coldfoot terrane, the structurally lowest unit in the orogen. In a fault system of this magnitude, fault slivers from all structural levels might be expected as tectonic lenses in the fault system. We suggest that the Rosie Creek sandstone is such a sliver.

Geologic map relations along the TACT route suggest that ductile and brittle normal faults are present in the Slate Creek terrane. The ductile faulting that formed the Slate Creek phyllonite occurred early and deformed primarily Coldfoot terrane rocks and locally chert-quartz arenite along the southern edge of the Slate Creek phyllonite. Tectonic mélange and narrow fault zones sharply truncate the phyllonite along its southern margin, indicating that the brittle deformation is relatively younger. This succession of events may be explained by normal faulting in a single fault system in which deformation of footwall rocks progressed from lower structural levels and higher temperatures to higher structural levels and lower temperatures as the footwall was tectonically unroofed. Cooling during the deformation is constrained by an $^{40}Ar/^{39}Ar$ white mica age of 113 ± 0.5 Ma (Early Cretaceous) from the Rosie Creek sandstone [*Blythe et al.*, 1996].

The east-west trending Malamute fault zone along the northern margin of the Koyukuk Basin and eastward along the northern edge of the Ruby terrane (Figure 1) is not exposed in the TACT study area. Its character and position are known only from a single exposure about 80 km west of the transect [*Dillon et al.*, 1986; *Dillon*, 1989]. The fault appears to mark the northern limit of mid-Cretaceous plutonism, which is widespread in central Alaska [*Miller*, 1994], suggesting that it may represent a fundamental post-mid-Cretaceous boundary. *Dillon* [1989] suggested that the Malamute fault links up with the Kobuk fault to the west, forming a structure that is at least 600 km long. On the basis of these relations, the Malamute is presumed to be a right-lateral strike-slip fault with at least 90 km [*Dillon*, 1989] and possibly hundreds of kilometers of displacement [*Grantz*, 1966; *Grantz et al.*, 1991]. The fault truncates Albian to Cenomanian strata and so is Late Cretaceous or younger.

Implications for Crustal Structure

Many workers have noted the general map pattern of progressively older and more metamorphosed rocks from north to south in the Brooks Range, from the Cretaceous Colville Basin to the Ordovician to Devonian and possibly older Skajit Limestone in the Hammond terrane (the Coldfoot terrane previously was assumed to be even older but is now known to be mainly Devonian along the TACT transect). *Dutro et al.* [1979] ascribed the systematic southward increase in age principally to superpositional relations in a deformed, but regionally northward dipping, Devonian to Cretaceous stratigraphic succession. Other workers, noting evidence for large-displacement thrust faults, such as the Amawk thrust in the Mount Doonerak antiform, instead have focused on structural boundaries in the orogen and modeled the Brooks Range as a series of fault slices, allochthons, or terranes [*Mull*, 1982; *Oldow et al.*, 1987; *Mayfield et al.*, 1988; *Dillon*, 1989; *Moore et al.*, 1994a]. The relation between the metamorphic core and the fold-and-thrust belt to the north is especially contentious; the amount of shortening implied across this boundary in some models is of the magnitude expected across a suture zone [e.g., *Dillon*, 1987]

New geologic mapping and observations presented here from the TACT transect support an interpretation that combines aspects of these various points of view into an integrated conceptual model (Figure 21). Interpretations key to this model include the following: (1) the Hammond terrane is allochthonous, (2) the Hammond terrane consists of depositional units that once lay stratigraphically below the Endicott Mountains succession, and (3) the Hammond terrane has structural patterns similar to those in the Endicott Mountains allochthon. These points are discussed below.

On the north flank of the Mount Doonerak antiform, the Amawk thrust lies beneath the Hammond terrane, above which is a detachment at the base of the Hunt Fork Shale (Figures 16 and 17). This detachment is shown as the southern limit of the Endicott Mountains allochthon in Figure 2 because it bounds structurally and stratigraphically more complex rocks below and to the south. However, the basal detachment of the allochthon is probably the underlying Amawk thrust, as suggested by *Mull et al.* [1987b]. The thin unit of Hammond terrane rocks beneath the Hunt Fork Shale pinches out along strike, indicating that the Amawk thrust merges northward with the detachment at the base of the

Hunt Fork (Figure 17). To the south, across the Mount Doonerak antiform, the Hammond terrane thickens and involves older rocks. This relation suggests that the Amawk thrust cuts down section beneath the Hammond terrane to the south. Along the southern margin of the Hammond terrane, the Hammond River phyllonite is a ductile fault that dips northward beneath the Hammond terrane. Although age data are limited for the units adjacent to the Hammond River phyllonite, the available data show that it and the Amawk thrust place older rocks onto younger rocks. On this basis, we suggest that the Hammond River phyllonite may mark the southern continuation of the Amawk thrust and that the Hammond terrane is entirely allochthonous. An allochthonous origin for the Hammond is supported by the juxtaposition of dissimilar sedimentary facies to the north (the Skajit Limestone against the lower Paleozoic clastic and volcanic arc rocks of the North Slope terrane in the Mount Doonerak antiform) and by the juxtaposition of terranes with different structural and metamorphic histories to the south (Hammond and Coldfoot terranes).

We have defined the boundary between the Hammond terrane and Endicott Mountains allochthon as the detachment fault that is at the base of the Hunt Fork Shale. This fault is a layer-parallel detachment that bounds stratigraphically related units above and below and is thus similar to the detachments in the Kayak Shale and Etivluk Group in the Endicott Mountains allochthon. This interpretation suggests that the Hammond constitutes the structural and stratigraphic lower part of the Endicott Mountains allochthon. Duplexes developed in the Skajit Limestone (e.g., Table Mountain and Snowden Mountain areas) show that deformation in the northern part of the Hammond is controlled, at least locally, by layer-parallel detachment surfaces that separate more competent rock units from less competent ones, as in the Endicott Mountains allochthon. Although separated by faults, a general progression to older rocks exists southward in the Hammond, from the Dietrich River phyllite to the Nutirwik Creek metavolcaniclastic rocks to the Skajit Limestone, all of which are older than the Hunt Fork Shale at the base of the Endicott Mountains allochthon to the north. The presence of ductily folded rocks and more thorough recrystallization in the southern part of the Hammond suggest that part of the terrane once existed at a deeper structural level than the imbricated rocks in the northern part of the Hammond and in the Endicott Mountains allochthon. This type of folding and degree of metamorphism further suggests that the basal part of the Hammond was deformed below or near the Early Cretaceous brittle-ductile transition.

Our age data support the possibility that Hammond terrane rocks were deposited in a stratigraphic succession beneath the passive margin sequence of the Endicott Mountains allochthon to the north, although depositional relations between most of the Hammond terrane units cannot be confirmed. These age data suggest that the oldest rocks in the Hammond are the Skajit Limestone. The Skajit includes a long-lived Ordovician to Devonian carbonate platform that was deposited on black, calcareous shale of the Lower and Middle Ordovician Snowden Creek phyllite. As presently defined, the Skajit may also include an older Proterozoic(?) and Cambrian carbonate platform that underlies the Ordovician shale [*Dumoulin and Harris,* 1994]. Carbonate platform deposition was probably terminated in the late Early Devonian by deposition of voluminous felsic tuffaceous deposits of the Nutirwik Creek metavolcaniclastic rocks. These units may then have been covered in the Middle(?) and early Late Devonian by fine-grained clastic rocks of the Dietrich River phyllite. The quartz- and chert-rich composition of the Dietrich River phyllite suggests that it represents basinal precursor deposits to the coarser grained clastic rocks of the Hunt Fork Shale, Noatak Sandstone, and Kanayut Conglomerate, which together make up the basal part of the Endicott Mountains allochthon. Assuming that the Hammond terrane rocks were deposited as a contiguous stratigraphic succession, structural relations require detachment horizons at the base of (1) the Skajit Limestone, (2) the Snowden Creek phyllite, (3) the Nutirwik Creek metavolcaniclastic rocks, (4) the Dietrich River phyllite, and (5) the Hunt Fork Shale (Figure 7). Although the Dietrich River phyllite consists of seemingly incompetent shale, it may have acted competently during deformation because of the abundant diabasic rocks that intruded and metamorphosed it.

Problems with interpreting the Hammond terrane as precursor deposits to Endicott Mountains allochthon rocks are that (1) competent units, such as the Skajit Limestone and bounding thrusts, are commonly laterally discontinuous in the Hammond terrane, (2) the youngest rocks of the Nutirwik Creek metavolcaniclastic rocks (middle Frasnian) are coeval with or younger than the lower part of the Dietrich River phyllite (Givetian(?) and lower Frasnian), (3) the feeder dikes for the mafic intrusive units in the Dietrich River phyllite have not been recognized in any of the older units, and (4) provenance characteristics vary markedly between adjacent units in the Hammond (e.g., Nutirwik Creek metavolcaniclastic rocks and metamorphosed sedimentary litharenites of the Trembley Creek phyllite).

The distribution of isolated carbonate massifs of the Skajit Limestone, thought to have once composed an extensive carbonate platform across northern Alaska [*Dumoulin and Harris*, 1994], is best explained by extensional deformation in the middle Paleozoic prior to contractional deformation in the Mesozoic. An episode of extension in the Middle(?) and Late Devonian is suggested by the abundance of mafic intrusive rocks with extensional geochemical characteristics in the Dietrich River phyllite. This unit also displays a record of subsidence from shallow-marine carbonates at its base to basinal clastic deposits at its top. Extension during the Middle(?) and early Late Devonian may have formed isolated local basins with distinct stratigraphies and provided local sources for clastic successions of restricted extent. Units that may represent stratigraphic fill of distinct, local basins in the Hammond terrane include the Dietrich River phyllite, Trembley Creek phyllite, Jesse Mountain phyllite, Vi Creek schist, and the metagraywacke and metaconglomerate unit (Figure 3b and Table 3). Magmas of extensional character may have intruded some of the Devonian basins that were underlain by thin crust but not adjacent areas of thicker crust. The extension proposed here for the Middle(?) and early Late Devonian may have followed regional arc magmatism and accompanied the continental breakup that led to the Upper Devonian to Lower Cretaceous passive-margin succession in the North Slope terrane and Endicott Mountains allochthon.

We conclude that the Endicott Mountains allochthon and Hammond terrane constitute a single allochthon whose basal detachment is beneath Skajit Limestone in the metamorphic core of the Brooks Range and progressively cuts up section northward in the hanging wall to Upper Devonian strata at the Mount Doonerak antiform (Figure 21), Mississippian strata east of Atigun Gorge, and Lower Cretaceous strata west of Elusive Lake. The basal detachment follows a footwall flat in Permo-Triassic strata for at least 90 km north of the Mount Doonerak antiform to near Elusive Lake. Detachments are principally stratigraphically controlled in the combined allochthon, and duplexing occurred between those detachments. The more complex stratigraphy in the Hammond terrane resulted in an apparently more complex and diverse style of deformation than in the Endicott Mountains allochthon. Detachments in the combined allochthon generally dip northward, resulting in a northward decrease in age of all units north of the Coldfoot terrane. A minimum displacement of 90 km is required to restore the combined allochthon, the same amount of displacement as for the Endicott Mountains allochthon alone, although this estimate does not account for internal deformation. The combined Hammond-Endicott Mountains allochthon is underlain by the Coldfoot terrane to the south and the North Slope terrane to the north. This implies that a structural contact of undetermined character exists between the Coldfoot and North Slope terranes at depth beneath the Hammond terrane because the Coldfoot and Hammond display very different stratigraphic, metamorphic, and structural characteristics.

Drop in Basal Detachment Over Time

The main phase of deformation in the Brooks Range is marked by thin-skinned deformation and the emplacement of allochthons, including ophiolite, in the northern Brooks Range and by the development of high-pressure, subduction zone metamorphic assemblages in the southern Brooks Range [*Moore et al.,* 1994a]. Along the TACT transect, the maximum age of emplacement of the combined Hammond-Endicott Mountains allochthon and the higher allochthons of the De Long Mountains terrane is constrained by the Valanginian (Early Cretaceous) age of the youngest strata involved in the deformation [*Mull et al.,* this issue]. The minimum age of emplacement is limited by the presence of clasts derived from the Endicott Mountains allochthon in the Albian Fortress Mountain Formation and the unconformable relations of the Colville Basin strata over allochthonous rocks outside the TACT study area. A late Neocomian (Early Cretaceous) age of allochthon emplacement is suggested by the subsidence history of the Colville Basin [*Cole et al.*,1994, this issue]. To the south, the age of high-pressure metamorphism in the southern Brooks Range has been difficult to date isotopically because of overprinting by younger greenschist-facies assemblages and the presence of older detrital-mica populations, but uplift-related cooling coincident with, or subsequent to, the high-pressure metamorphism is indicated by the 130 to 120 Ma Ar-Ar white-mica ages reported from the Coldfoot terrane [*Blythe et al*., 1996]. The concurrence of allochthon emplacement and high-pressure metamorphism along the TACT route in the Neocomian suggests a link between tectonic events in the southern and northern Brooks Range. Deformation associated with subduction zone metamorphism of deeper level rocks to the south may have been coupled to fold-and-thrust deformation to the north in part by displacement along the base of the combined Hammond-Endicott Mountains allochthon. No evidence exists to indicate Early Cretaceous deformation of parautochthonous rocks at least as far south as the Mount Doonerak antiform, so the base of the combined allochthon may have acted as the basal detachment for the Early Cretaceous deformation.

Abundant evidence exists, however, that the combined Hammond-Endicott Mountains allochthon was deformed by younger structures. To the south, the Wiseman thrust truncates the trailing edge of the allochthon. Younger folds, such as the Snowden Creek synform, Mount Doonerak antiform, and Ribdon River anticlinorium, deform the combined allochthon. The Atigun syncline and the Atigun Gorge back thrust both involve Albian (late Early Cretaceous) rocks and the allochthon. All of these structures deform the detachment at the base of the combined Hammond-Endicott Mountains allochthon and hence root at a deeper structural level. Structural relations in the Mount Doonerak and the Ribdon River antiforms and TACT seismic data indicate that the faults in the core of these structures are located deep in pre-Mississippian rocks of the North Slope terrane [e.g., *Oldow et al.,* 1987; *Levander et al.,* 1994; *Fuis et al.,* 1995, this issue; *Wallace et al.,* this issue]. Fission track analyses indicate that the Mount Doonerak antiform originated at 70 to 60 Ma (Maastrichtian to Paleocene) and was reactivated at about 24 Ma (Oligocene) [*Blythe et al.,* 1996; *O'Sullivan et al.,* 1997].

Seismic reflection and refraction data collected as part of TACT investigations show two sets of relatively bright reflectors under the northern Brooks Range [*Levander et al.,* 1994; *Fuis et al.,* 1995]. The first is present at a depth of ~6 km beneath the Endicott Mountains allochthon and approaches the surface near the Mount Doonerak antiform (Figure 21). This set is interpreted to image carbonate rocks of the Lisburne Group below the base of the Endicott Mountains allochthon [*Fuis et al.,* 1995]. The second set consists of a series of southward dipping en echelon reflectors that terminate downward in pre-Mississippian rocks at a depth of ~12 km under the northern Brooks Range. These reflectors are interpreted to mark horses that root in an underlying basal detachment at the lower termination of the reflectors. Thus defined, this basal detachment can be traced from a depth of about 10 km in the northern part of our study area to ~25 km beneath the Mount Doonerak antiform, where the detachment appears to form a crustal-scale ramp beneath the antiform (Figure 21). This relation suggests that displacement along the basal detachment resulted in uplift and erosion in the Mount Doonerak antiform at 70 to 60 Ma and ~24 Ma, as determined from the fission track studies. Horses imaged by the seismic data are likely expressed at the surface as the long-wavelength folds that deform older fabrics, such as the Snowden Creek synform, the Mount Doonerak antiform, and the Ribdon River anticlinorium, and as faults that truncate older structures, such as the Wiseman thrust and the Atigun Gorge back thrust. Northeast of our study area in the northeastern Brooks Range, fission-track studies indicate episodic uplift-related cooling at ~60, ~45, ~35, and ~25 Ma [*O'Sullivan et al.*, 1993a, this issue], suggesting that deformation in the northeastern Brooks Range is linked to north directed thrusting in the central Brooks Range above the basal detachment in pre-Mississippian rocks. Displacement along the basal detachment is interpreted to terminate northward in one or more Late Cretaceous or Tertiary triangle zones with backthrusts commonly localized near the base of the Brookian sequence, such as the triangle zone that deforms the earlier formed structural stratigraphy in the Elusive Lake area.

This analysis suggests that an upper detachment surface at the base of the combined Hammond-Endicott Mountains allochthon represents the basal thrust for Early Cretaceous deformation, whereas a lower detachment surface is the basal detachment for Tertiary age thrusting in the Brooks Range (Figure 21). Deformation above the upper detachment is thin-skinned because it involves primarily sedimentary cover units; deformation above the lower detachment is thick-skinned because it involves basement rocks that have poorly defined, metamorphosed, and previously deformed stratification. Apatite fission track data along the TACT transect from the metamorphic core to the Colville Basin indicate significant uplift and unroofing since ~60 Ma [*O'Sullivan et al.*, 1993b, 1997, this issue; *Blythe et al.*, 1996; *O'Sullivan*, 1996]. Thus the modern Brooks Range formed by Tertiary deformation and uplift of an older, Early Cretaceous mountain belt [*Moore et al.*, 1994b; *O'Sullivan*, 1996; *O'Sullivan et al.*, this issue]. This analysis explains why the Brooks Range forms the northward extension of the Late Cretaceous to Tertiary Rocky Mountains orogen, although most work has suggested a Late Jurassic and Early Cretaceous age for main phase Brooks Range deformation [*Moore et al.*, 1994b].

Conclusion

Published cross sections through the Brooks Range along the Dalton Highway [e.g., *Mull et al.* 1987a; *Oldow et al.*, 1987; *Grantz et al.*, 1991; *Moore et al.*, 1994a; *Blythe et al.*, 1996] are all based primarily on the same first-generation, small-scale (1:250,000) reconnaissance geologic maps published from 1964-1986. Although these maps and sections generally offer a consistent image of the crustal structure of the Brooks Range, the results of newer and more detailed (1:63,360 scale) mapping presented here provide a more comprehensive understanding of the geology of the Brooks Range and its crustal structure. Among the significant new findings of this mapping are that (1) the Slate Creek terrane is a fundamental tectonic unit developed by mid-Cretaceous, down-to-the-south normal faulting, first in a ductile regime and then later in a brittle regime; (2) the protoliths of two of the major rock units of the Coldfoot terrane are Silurian to Devonian and possibly younger sedimentary rocks rather than Proterozoic or early Paleozoic rocks as previously thought; (3) orthogneiss intrusions in the Coldfoot terrane are Early Devonian and display evidence of generation as subduction zone magmas; (4) the northern limit of the Coldfoot terrane is a north dipping ductile shear zone about 10 km north of the south dipping fault that previously was thought to form the northern limit of the terrane; (5) the Hammond terrane consists of lower and middle Paleozoic rocks that are allochthonous and overlie younger rocks of the Coldfoot and North Slope terranes; (6) the Hammond terrane consists principally of metamorphosed Ordovician, Silurian, Devonian, and possibly Upper Proterozoic and Cambrian carbonate rocks; Lower Devonian felsic volcaniclastic rocks; and Upper Devonian basinal clastic rocks with mafic intrusions; (7) the rocks assigned to the Skajit Limestone along the TACT transect are mostly significantly older than the published age of that formation; (8) the Beaucoup Formation consists of at least two distinct, mappable units in the TACT transect; (9) the Hammond terrane wedges out northward above the North Slope terrane and below the Endicott Mountains allochthon; (10) deformation in the Endicott Mountains is characterized by duplexes in competent units bounded above and below by layer-parallel detachments; (11) the Toyuk thrust system breaches these layer-parallel detachments, in places, and juxtaposes distinctly different facies in Devonian and Carboniferous rocks, suggesting relatively large displacement for the structure; (12) the basal thrust of the Endicott Mountains allochthon can be identified in the northern Brooks Range by stratigraphic differences across the thrust in the Lisburne Group and Permian and Triassic units; (13) the basal thrust of the Endicott Mountains allochthon rests on a décollement developed in Permian and locally Triassic strata rather than Cretaceous strata as previously suggested; (14) a nested triangle zone, comprising an older zone developed in the Early Cretaceous and a younger one formed in the Late Cretaceous or Tertiary, is present along the northern range front of the Brooks Range; and (15) the Hammond terrane and Endicott Mountains allochthon and their basal detachments have been folded by underlying structures.

These conclusions and observations provide the basis for considerable revision of existing models for the structure and evolution of the Brooks Range. We suggest that the Hammond terrane and Endicott Mountains allochthon constitute a single allochthon that rests on rocks of the Coldfoot terrane to the south and the North Slope terrane to the north. The basal thrust of the combined allochthon is a ductile fault zone in the southern Brooks Range. This fault climbs up section in the hanging wall through the lower and middle Paleozoic rocks of the Hammond terrane, where it is called the Amawk thrust, to a detachment at the base of the Hunt Fork Shale and then up section northward through the Kanayut Conglomerate and Lisburne Group to condensed Jurassic and Lower Cretaceous shale at its northern termination in the northern foothills of the Brooks Range. For the entire distance from Mount Doonerak to its northern exposed limit, the combined allochthon rests on a footwall flat in Permian and Triassic shale near the top of the Echooka Formation and locally within or above the Shublik Formation. Stratigraphic data indicate that the allochthon was emplaced between the Valanginian and Albian, so the allochthon cannot have been thrust above Albian and younger foredeep deposits of the Colville Basin, as some models show. Minimum displacement of the combined allochthon, at least 90 km, is the same as that determined for the Endicott Mountains allochthon alone [*Mull et al.*, 1987b].

The revised tectonic model suggests that strata of the Endicott Mountains allochthon were originally deposited on now metamorphosed and dismembered units of the Hammond terrane, providing new insight into the depositional history of the Arctic Alaska superterrane: Carbonate platform sedimentation, recorded in basal Hammond terrane rocks, was long-lived in the early Paleozoic and was terminated in the Early Devonian when voluminous, felsic, subduction-related volcanism, documented in the middle Hammond, began. Extensional tectonism of the upper Hammond in the Middle and/or Late Devonian followed the felsic volcanism and caused block faulting that disrupted the older carbonate platform and opened isolated basins into which mafic magmas were intruded. The extensional tectonism culminated in continental breakup in the latest Devonian or Early Mississippian and the development, chronicled in the Endicott Mountains allochthon, of a subsiding passive-continental margin that lasted from the latest Devonian to the Early Cretaceous.

The extent of the basal thrust of the combined Hammond-Endicott Mountains allochthon across strike from a ductile shear zone beneath lower Paleozoic rocks in the south to a brittle fault beneath Lower Cretaceous strata in the north, and the presence of underlying parautochthonous rocks for much of its extent, suggest that the basal thrust may mark the base of Early Cretaceous deformation in the northern Brooks Range. This thrust is folded by younger structures, such as the Mount Doonerak antiform, that root at a deeper level of detachment well imaged by TACT seismic data. Fission track ages date cooling that is ~60 Ma and younger and probably reflect displacement on this detachment that led to the uplift and unroofing of the modern Brooks Range. Thus the modern Brooks Range is a latest Cretaceous and younger orogen that has uplifted and exposed an older, Late Jurassic to Early Cretaceous orogen that has long been considered the expression of the main deformational phase of the Brookian orogen.

A major remaining enigma concerning the evolution of the Brooks Range is the palinspastic restoration of the Coldfoot terrane. As discussed by *Moore et al.* [this issue], this terrane may represent either the southern extension of the North Slope parautochthon or, alternatively, an outboard part of the Arctic Alaska terrane that was wedged northward beneath the combined Hammond-Endicott Mountains allochthon during Early Cretaceous deformation. In either case, the Coldfoot terrane has seen intense deformation and high-pressure metamorphic conditions not imposed on terranes farther north. Subsequently, in the mid-Cretaceous, the Coldfoot terrane was extensively and rapidly exhumed, probably by extensional unroofing. Whether this extension was a consequence of contractional deformation, as proposed by *Gottschalk and Oldow* [1988], or regional tectonic extension, as proposed by *Miller and Hudson* [1991], is unclear. Much of the extensional unroofing may have been related to the complex normal fault zone in the Slate Creek terrane, but the northward extent of extensional fabrics and structures remains controversial. Extensional deformation may have produced the prominent south dipping foliation present throughout the Coldfoot terrane [*Little et al.*, 1994] and reactivated the ductile fault zone in the Hammond River phyllonite which bounds the northern margin of the Coldfoot terrane.

The conceptual models discussed here suggest that deformation in the Brooks Range, as in other orogenic belts, progressed sequentially away from the core of the orogen through time from thin-skinned deformation of cover rocks to thick-skinned, basement-involved deformation. The likelihood that structures in the Brooks Range developed during two distinct orogenic phases will make it difficult to determine when specific structures were active and thus will pose a significant challenge for the construction of balanced cross sections. During the time between the two major orogenic episodes, extensional unroofing in the southern Brooks Range, large-displacement right-slip deformation along the Malamute fault, and continued sedimentation along the margins of the orogen may have occurred, all of which bear on the assumptions about conservation of area required to construct balanced sections. Where deformation was by plane strain and no important tectonic events occurred between the two orogenic episodes, such as in the northern part of the transect, balanced sections might still be meaningful, although the kinematic history of different generations of structures (for example, the nested triangle zones in the Elusive Lake-Atigun Gorge area) may be difficult to resolve. In the southern Brooks Range, however, the possibility of several intervening tectonic events, in addition to the complex stratigraphy resulting from a mid-Paleozoic episode of extension and possible volume loss due to Brookian metamorphism, greatly increases the uncertainty of balanced sections. These complications suggest that the validity of balanced cross sections across at least the southern part of the orogen should be assessed with caution.

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